# RAPID, PREDICTIVE MODELING FOR HIGH FREQUENCY INTERCONNECT ON LOW COST SUBSTRATES

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Presented to
The Academic Faculty

By

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# RAPID, PREDICTIVE MODELING FOR HIGH FREQUENCY INTERCONNECT ON LOW COST SUBSTRATES

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# DEDICATION

***I would like to dedicate this work to God***

***and***

***my lovely, precious wife, Kiyeon.***

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# SUMMARY

In this dissertation, a predictive (scalable) measurement-based PEEC modeling method for high-frequency interconnects on low-cost FR4 substrates is proposed and demonstrated. The interconnects are modeled with equivalent circuits of scalable building blocks using a rapid and accurate optimization method to fit parameter data up to 10 GHz. The predictive power of the developed scalable models is demonstrated in several extended interconnect structures and the ability to use interpolation to predict the high frequency performance of structures with differently sized building blocks is demonstrated. The usefulness of the proposed modeling method is validated by comparing predictions to measurements both in frequency domain and in time domain. The efficiency and accuracy of the method are also compared with the Advanced Design System (ADS) momentum simulation tool. The results show that this proposed high-frequency interconnect modeling method is very much more efficient in terms of simulation time, while maintaining comparable accuracy, compared to momentum simulations and measured behavior.

This thesis work represents two significant contributions that address the challenges of high speed of the electrical board-level interconnect design. First, the development of a very fast predictive measurement-based modeling method to accurately predict electrical board-level interconnects on low-cost FR4 board. Second, demonstration that the prediction of interconnect models using interpolation between measured building blocks is also accurate, thus enabling fast accurate simulations with variations in width and spacing of the interconnect.

# CHAPTER I

## INTRODUCTION

Relentless advances in on-chip technologies, directly influencing board-level interconnects, have whetted end users' appetite for miniaturization and acceleration. Consequently, high-frequency, volume-manufactured digital designs need to meet timing budget in pico-second ranges. This means that board-level interconnects have become transmission lines [1-3]. Historically, transmission lines have been used in the domain of microwave systems that use narrow bandwidths; however, in high-frequency digital systems, broad signal bandwidths have to be considered because a digital signal has a spectrum similar to white noise spread from well below the data rate (perhaps from DC for unencoded data) to as high as five or ten times the data rate depending on the rise time of the signal.

As operating frequencies need to be increased to satisfy requirements in a system, non-ideal effects such as skin effect and frequency dependent dielectric loss have increasingly significant impacts on an interconnect system [3-8]. In a digital interconnect system, since these non-ideal effects vary with frequency, it is difficult to accurately take them into account with the time domain tools which are used by most circuit designers to estimate timing information and confirm signal integrity. This suggests that modeling methodologies with the potential to incorporate measured frequency dependent material properties are important. Particularly, challenging is to use the FR4 board at data rates over 1 Gbps (Giga-bit per second) because of high losses and frequency dependent

effects, and the propensity of statistical variations to invalidate carefully designed impedances.

The current approach used to deal with high frequency transmission line interconnect design is either numerical electromagnetic finite element (FE) based modeling tools, or equation based transmission line models. Unfortunately the FE based modeling tools suffering from high computational cost (significant computer resources and long simulation time), and the equation based models lack accuracy for complex geometry or unknown material properties [6, 30, 52, 55]. The goal of this research is to develop a new, accurate, predictive, and very time efficient way of modeling transmission line interconnect on printed circuit boards, with the application of 10 Gbps data transmission as a focus. The non-ideal behavior of the FR4 printed circuit board material at high frequencies makes this a challenging task. It will be shown the method developed has the accuracy of the best commercial finite element tools, is flexible, allowing dimensions of the interconnect to be varied, including line to line spacing, and is very fast compared to the finite element methods.

In this work, high-frequency interconnects are modeled with equivalent circuits each represented by a building block using rapid and accurate optimization to determine the parameters of the equivalent circuits. A prototype equivalent circuit is made from a partial element equivalent circuit (PEEC) that is derived from the electric field integral equation (EFIE) [38-46]. Then, an equivalent circuit is obtained by modifying the prototype circuit according to the geometrical variations. The accuracy of this building block approach was previously demonstrated on passive devices [50, 51]. Meanwhile, to our best knowledge, no work has been reported on using this method on FR4 board or

interpolation between different structures, to allow the designer to use arbitrary dimensions for the interconnect, both of which will be explored in this dissertation.

The case studies in Chapters 4 and 5 show that prediction using building blocks is an applicable way to model the two indispensable interconnection elements on the FR4 board: a straight microstrip line and a serpentine structure, respectively. Then, the usefulness of the modeling methodology is validated by comparing the prediction with response measurements both in the frequency domain and in the time domain. The efficiency and accuracy of the method are also compared with those of the Advanced Design System (ADS) momentum tool which has predictive modeling capability [36]. Additionally, Chapter 5 verifies prediction by interpolation. These collective results of the modeling indicate that predictive modeling using building blocks and using interpolation are applicable ways to model high-frequency interconnects on FR4 board.

This thesis work has two new contributions that can address the limitations of electrical board-level interconnects. First, a predictive measurement-based PEEC modeling method is applied to electrical board-level interconnects on low-cost FR4 board. Second, predictive interpolation between the measured PEEC models is demonstrated allowing interconnect dimension not measured to be modeled.

## 1.1. Thesis Organization

This dissertation mainly focuses on developing a rapid measurement-based modeling model for board-level interconnects, then applying for predicting other extended structures by scalability and interpolation. It has two main parts: background

and technical approach (Chapter 2-3), and case studies of the proposed methodology (Chapter 4-5). In the first part, trends and limitations of high-frequency board-level interconnect give motivation to this work. A review of general modeling methodologies, also, assists in understanding of the following description of measurement-based PEEC modeling methodology. In the second part, two cases that include essential board-level interconnect elements demonstrate the efficiency and usefulness of the proposed methodology. Now, a brief description of the thesis by chapters is provided below.

In Chapter 2, the forecast of on-chip and off-chip frequency trends from the 2003 international technology roadmap for semiconductor (ITRS) presents the motivation for modeling FR4 material-based technology; the limitation factors of high frequency interconnect on FR4 board are described with surveys, simulations and experiments. This chapter also covers general modeling approaches, classified into three types: analytical equation-based approach, numerical full-wave-based approach and measurement-based approach. Chapter 3 discusses motivation and overall procedure of the predictive measurement-based PEEC modeling method.

With the method described in Chapter 3, Chapter 4 shows a demonstration of the method applied to straight microstrip lines of different lengths. In the same manner, a more advanced case study, the modeling of serpentine interconnect on FR4 board, is described in Chapter 5. Both Chapter 4 and Chapter 5 present model predictions and performance comparisons with the ADS momentum tool in terms of accuracy and simulation time. In addition, Chapter 5 provides contains the development of prediction by interpolation. Chapter 6 concludes and summarizes the thesis work and shows the

direction of future works. Appendices provide measured data and simulation information for the guidance of those who might like to duplicate this work.

# CHAPTER II

# BACKGROUND

## 2.1. Introduction

With system frequency increasing dramatically, it is no longer applicable in high-frequency digital systems to think of interconnect as lumped capacitors or simple delay channels. Accordingly, designers now have to model board-level signal paths as transmission lines. To achieve such a modeling work, an understanding of theoretical transmission line background and practical PCB design knowledge are necessary. In this chapter, the theoretical background of high-frequency interconnects is reviewed in light of current high-frequency board-level interconnect trends and limitations and also current widely used modeling methodologies.

## 2.2. Trends of High-frequency Interconnect on Board

Major progress has been made in semiconductor technology since circuits were integrated onto silicon substrates, thus decreasing exponentially the minimum feature size of a transistor by advanced fabrication technologies [1-3]. The reduced size contributes to increasing the operating frequency and decreasing the integration area and the cost per function. However, these high-frequency signals generated by a chip propagate onto a physically much larger printed circuit board, requiring transmission line interconnect.

Moreover, the lowest cost printed circuit boards suffer from non-ideal effects [4-8] that make the interconnect modeling even more challenging.

The 2003 ITRS technology roadmap [3] shows two interesting forecasts presented in Figure 2.1. First, on-chip frequency and off-chip frequency will meet around 2017 with the advent of new advanced material technologies. Second, it is forecast that in the near term the trend of off-chip interconnects will be to keep their speed lower than 10 GHz. The second forecast, more interesting to us, is due to a market trend: most telecommunication companies have preferred the use of the low-cost FR4 laminates that may not guarantee performance over 10 GHz as they were not fabricated for the purpose of high frequency signal propagation.

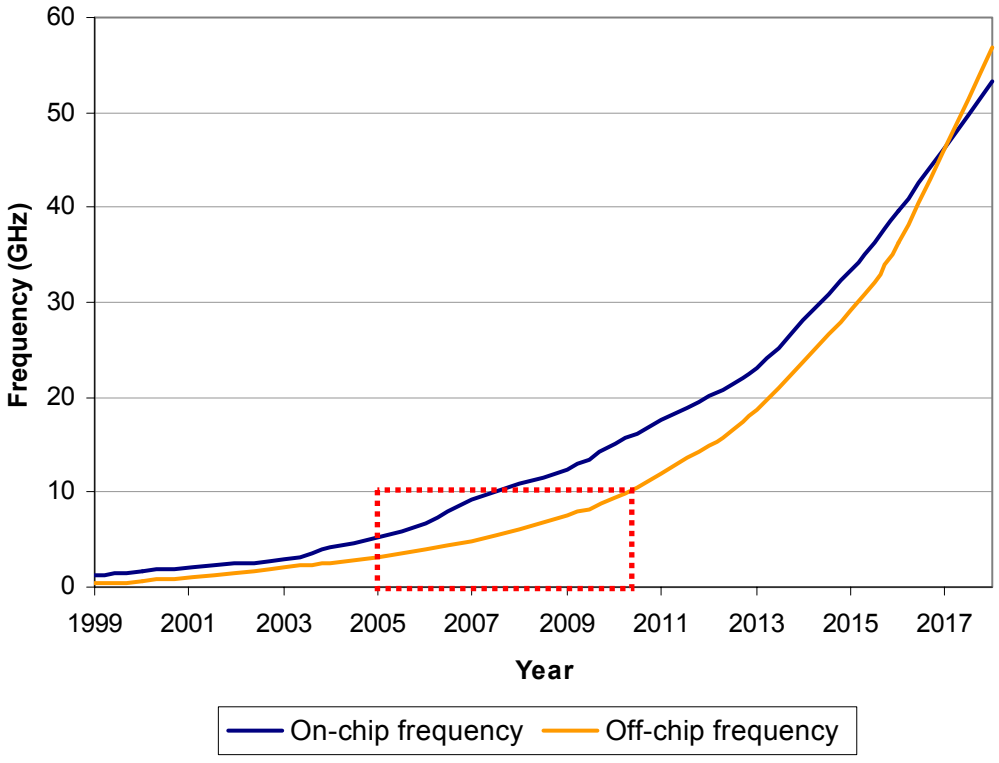
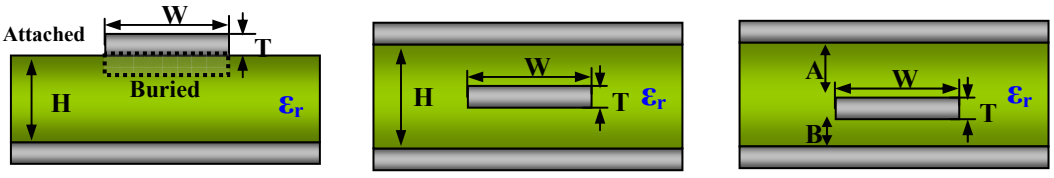



Figure 2.1. Trend of on-chip frequency and off-chip frequency.

Furthermore, considering that cost-performance and low-cost products occupy a considerable area of the market, interconnects on FR4 board are still an attractive, lasting technology. FR4 laminates however need more design work to achieve acceptable electrical performance at speeds of 10 Gbps than other (more expensive) materials, as will be considered in Section 2.4.2.1 [7-9]. Hence, interconnects on FR4 should be designed with rapid, accurate models to satisfy the high-frequency signal integrity requirements.

## 2.3. Lossy Transmission Line

In general, a transmission line consists of insulating layers of dielectric materials and metal layers that play the roles of conductive paths and reference planes buried in or attached to the dielectric materials. Two types of transmission lines pervasively used in digital systems are a microstrip and a stripline. Metal traces of the microstrip line are buried in layers or attached on an external layer and are electromagnetically correlated with a single reference plane, as shown in Figure 2.2 (a). Metal traces of the stripline are inside an insulating layer and are electromagnetically correlated with two reference planes. A stripline can be classified as a symmetrical stripline or an offset stripline, as shown in Figure 2.2 (b) and (c), respectively.




(a) Microstrip (b) Symmetrical stripline (c) Offset stripline

Figure 2.2. Cross-section view of transmission lines.

When a signal propagates on a transmission line, it travels in accordance with a voltage difference between the signal path and the reference plane. In other words, when a signal meets a transmission line of different impedance ($Z_0$), the signal path and reference plane have potentials of Vi (V) and 0 (V), as shown in Figure 2.3 [6]. This potential difference between the signal and the reference induces an electric field. Besides, a current incoming through a signal path results in a magnetic field around the transmission line based on the Biot-Savart's law. Thus, the behavior of a transmission line is characterized in terms of the electric field and the magnetic field between the signal path and the reference plane.

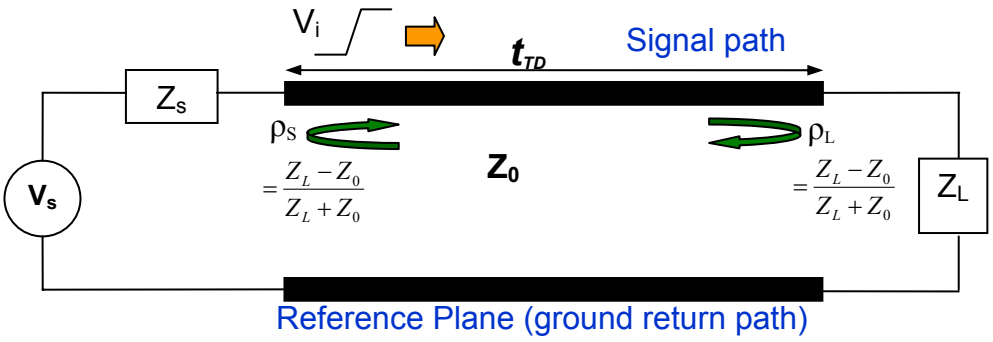



Figure 2.3. Diagram of signal propagation on transmission lines.

In a case where an electric field and a magnetic field do not have the Z-direction component, which means the two fields are orthogonal, it is called the transverse electro-magnetic mode (TEM). This mode is an interpretation of propagation that allows the application of approximate equivalent circuit models (RLGC elements) along the Z-direction. The electrical properties of a transmission line are characterized by the characteristic impedance ($Z_0$) and the propagation velocity ( $v$ ). In the subsequent

subsections, the characteristic impedance and the propagation velocity are described with fundamental and practical equations formulated by early researchers [10-20].

### 2.3.1. Characteristic impedance

The characteristic impedance of a transmission line is defined as the ratio of the voltage wave to the current wave at any point of the transmission line. In practice, the characteristic impedance of the transmission line can be expressed by the RLGC element, which is a differential section of the transmission line as given by Equation 2.1 and as shown in Figure 2.4:

$$Z_0 = \frac{V}{I} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \ , \tag{2.1}$$

where $R$, $L$, $G$, $C$, and $\omega$ are in ohms per unit length, in henries per unit length, in siemens per unit length, in farads per unit length, and in radians per second, respectively.

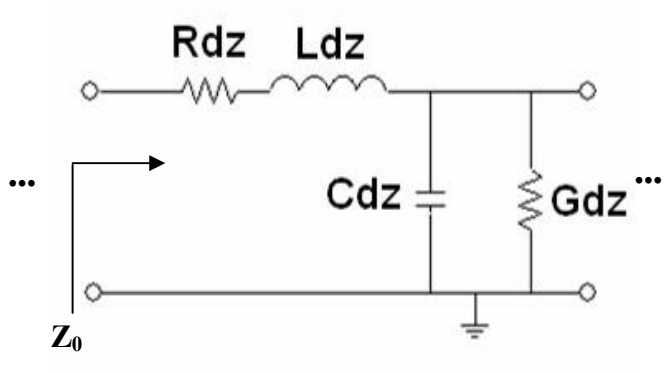



Figure 2.4. RLGC elements of the transmission line of length *dz*.

Among RLGC elements, the loss factors, R and G, are not relatively dominant. However, these factors significantly affect the characteristic impedance at very high frequencies or on very lossy lines. In more practical applications, considerable efforts have been made to derive simple, practical formulas that are based on approximate analytic solutions, along with empirical adjustment using various numerical methods [13-19].

Among these results, a set of Equations 2.2, 2.3, 2.4, and 2.5 defines the characteristic impedance of a microstrip line, which is accurate in the geometric range of $0.25 \leq W/H \leq 6$ and $1 < \varepsilon_r \leq 16$ [14]. The effective dielectric constant is considered for a microstrip line, as given by Equation 2.4, because the electric field and the magnetic field between signal paths and reference planes propagate in two different media, air and insulating materials [15, 18]:

$$Z_{0micro} = \sqrt{\frac{\mu_0 \varepsilon_0}{\varepsilon_e}} \frac{1}{C_a}, \tag{2.2}$$

where $C_a$ and $\varepsilon_e$ are defined as

$$C_a = \begin{cases} \dfrac{2\pi\varepsilon_0}{\ln\left(\dfrac{8H}{W} + \dfrac{W}{4H}\right)} & case: \dfrac{W}{H} \leq 1 \\ \varepsilon_0 \left[\dfrac{W}{H} + 1.393 + 0.667 \ln\left(\dfrac{W}{H} + 1.444\right)\right] & case: \dfrac{W}{H} > 1 \end{cases}, \tag{2.3}$$

and

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12H}{W}\right)^{-0.5} + F - 0.217(\varepsilon_r - 1)\frac{T}{\sqrt{WH}}. \quad (2.4)$$

In Equations 2.2, 2.3, and 2.4,

$$F = \begin{cases} 0.02(\varepsilon_r - 1)\left(1 - \frac{W}{H}\right) & case: \frac{W}{H} \le 1 \\ 0 & case: \frac{W}{H} > 1 \end{cases}, \quad (2.5)$$

where $W$, $T$, and $H$ are the metal width of the signal path, metal thickness, and dielectric material thickness, respectively, as shown in Figure 2.2, and $\mu_0$, $\varepsilon_0$, and $\varepsilon_r$ are the permeability of free space ($4\pi\times10^{-7}$ H/m), the permittivity of free space ($8.854\times10^{-12}$ F/m), and the dielectric constant, respectively. $Z_{0micro}$, $C_a$, $\varepsilon_e$, and $F$ are the characteristic impedance of the microstrip, the effective dielectric constant, the capacitance of the unscaled air-filled line and a numerical coefficient for Equation 2.4, respectively.

A stripline, on the other hand, uses only the relative dielectric constant as given by Equation 2.6 because the fields are completely confined inside the insulating materials between the two reference planes. Equation 2.6 and Equation 2.8 represent the characteristic impedances of the symmetrical stripline and the offset stripline [19, 20]. These formula sets are accurate in the geometric range of $T/H < 0.25$ and $T/W < 0.11$:

$$Z_{0sym} = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_r}} \ln \dfrac{4H}{\pi K_1} & case: \dfrac{W}{H} < 0.35 \\ \dfrac{94.15}{\sqrt{\varepsilon_r}\left(\dfrac{W}{H-T} + \dfrac{K_2}{\pi}\right)} & case: \dfrac{W}{H} > 0.35 \end{cases}, \tag{2.6}$$

where $K_1$ and $K_2$ are defined as

$$\begin{aligned} K_1 &= \left(\frac{W}{2}\right)\left[1 + \frac{T}{W\pi}\left(1 + \ln\frac{4\pi W}{T}\right) + 0.255\left(\frac{T}{W}\right)^2\right] \\ K_2 &= \frac{2}{1-T/W}\ln\left(\frac{1}{1-T/W}+1\right) - \left(\frac{1}{1-T/W}-1\right)\ln\left(\frac{1}{(1-T/W)^2}-1\right) \end{aligned}, \tag{2.7}$$

and $Z_{0sym}$ is the characteristic impedance of the symmetrical stripline.

As given in Equation 2.8, the characteristic impedance of the offset stripline is calculated utilizing Equations 2.6 and 2.7:

$$Z_{0offset} = 2\frac{Z_{0sym}(H_1, W, T, \varepsilon_r) Z_{0sym}(H_2, W, T, \varepsilon_r)}{Z_{0sym}(H_1, W, T, \varepsilon_r) + Z_{0sym}(H_2, W, T, \varepsilon_r)} \tag{2.8}$$

$$H_1 = 2B + T, \qquad H_2 = 2B + T, \tag{2.9}$$

where $Z_{0offset}$ is the characteristic impedance of the offset stripline, $A$ and $B$ are the dielectric material thicknesses from a signal path to an upper reference plane and from a signal path to a lower reference plane, respectively, and $H_1$ and $H_2$ are substitution variables into Equation 2.8.

### 2.3.2. Propagation velocity

Electric and magnetic waves on a transmission line travel at a specific propagation velocity, which is inversely proportional to the square root of the dielectric constant of media, as given by Equation 2.10 [10, 24]:

$$v = \frac{c}{\sqrt{\varepsilon_r}}, \tag{2.10}$$

where $v$, $\varepsilon_r$, and c are the propagation velocity in meters per second, the dielectric constant, and the speed of light in free space ($3\times10^8$ m/s). The reciprocal of the propagation velocity delay is the propagation delay, which stands for the delay time of a transmission line per unit meter. Thus, the time delay of the transmission line, which is the traveling time from one end of a link to the other end, is simply obtained by the product of the propagation delay and the traveling distance in meters as given by Equation 2.12 [10, 24]:

$$PD = \frac{1}{v} = \frac{\sqrt{\varepsilon_r}}{c}, \tag{2.11}$$

and

$$t_{TD} = \frac{x\sqrt{\varepsilon_r}}{c}, \tag{2.12}$$

where $PD$, $t_{TD}$, and $x$ are the propagation delay in seconds per meter, the time delay in seconds, and the distance of the transmission line in meters.

The propagation velocity, the propagation delay, and the time delay are functions of the dielectric constant. If the electric field and magnetic field encounter discontinuity of the propagation media, the dielectric constant is substituted for the effective dielectric constant ( $\varepsilon_e$ ), as in the case of the microstrip mentioned in Equation 2.4.

## 2.4. Limitations of High-frequency Interconnect on Board

As the demand for high data rate and denser integration increases in digital systems, non-ideal interconnect issues, which have been ignored at lower frequency and in affordable areas, become notable concerns. Besides such the intrinsic issues, geometrical design issues, such as long line, couplings and geometrical discontinuities, have a significant impact on interconnection performance. Herein, several non-ideal issues of high-frequency interconnects are reviewed by fundamental equations and simulation results, and geometrical design issues are review by references and experiments.

### 2.4.1. Non-idea effects

#### 2.4.1.1. Skin effect

The skin effect is expressed in terms of resistance variations and inductance variations [21, 22]. At low frequencies, these terms represent only DC values, but at high frequencies, they behave as frequency-dependent variables [23]. From the viewpoint of current density, as frequencies increase, the cross-sectional current

distribution in the transmission line is confined to the surface region. Variations of current distribution with frequency change increase the resistance in proportion to the square root of the frequency and make the total inductance statistic. Amplitude of current density is attenuated by a factor of $e^{-1}$ of the initial current density [24]. A measure of the skin effect is the skin depth, which is a conductor thickness that maintains the attenuation factor and is computed by Equation 2.13:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0}} = \sqrt{\frac{\rho}{\pi F \mu_0}} \quad (m), \tag{2.13}$$

where $\rho$, $\omega$, and $\mu$ are the resistivity of the conductor, the angular frequency in radians per second, and the permeability of free space ($4\pi\times10^{-7}$ H/m).

Analysis of the skin depth of a microstrip in order to see the skin effect is performed in a broad frequency range, as shown in Figure 2.5. The result indicates that the skin effect needs to be considered when the skin depth is less than the conductor thickness, and this effect is significant at high frequencies because of thin skin depths.

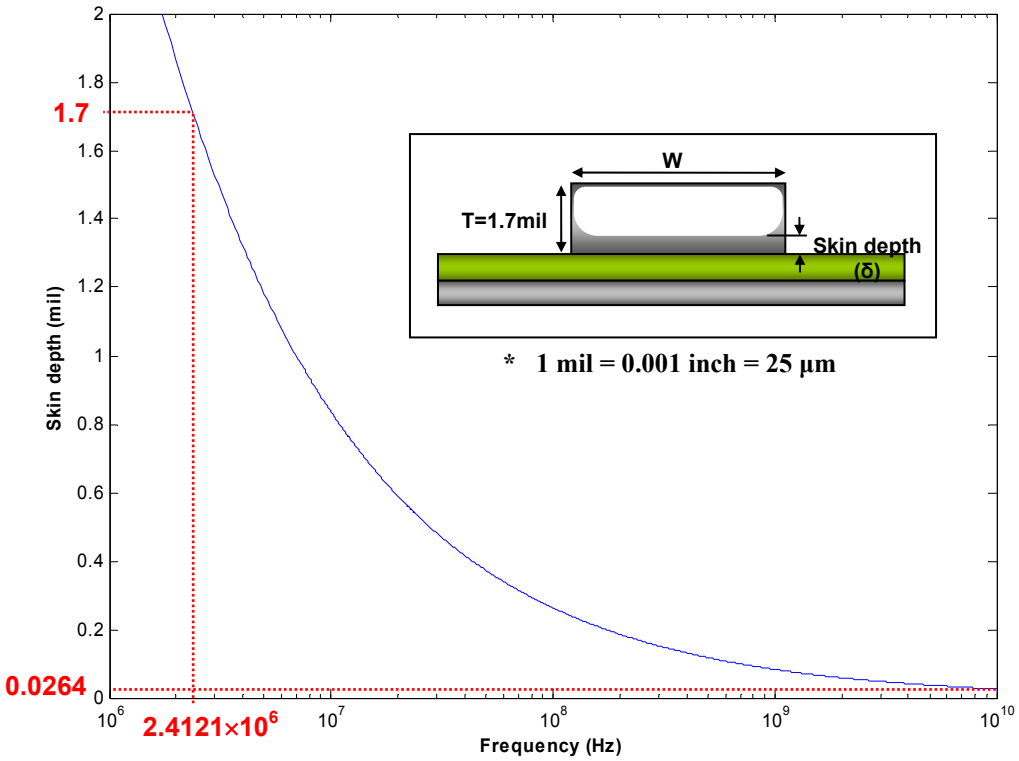



Figure 2.5. Skin depth as a function of frequency.

### 2.4.1.2. Frequency-dependent dielectric loss

Dielectric loss is negligible at low frequencies because of the comparatively dominant conductor loss factor. However, as frequency increases, the dielectric loss becomes a significant factor in the signal transmission. It is necessary to comprehend the fundamental mechanism of frequency-dependent dielectric losses. Once electric fields varying with frequency travel onto a dielectric material, polar molecules in the material experience so-called electric polarization [25, 27]. The experience is simply explained by a phenomenon where the polar molecules in the material have a tendency to align in the opposite direction to the applied electric field. This tendency gives rise to the mechanism

of the damping and resonance in the high-frequency range, thus changing the dielectric constant [26, 27]. Note that whereas the dielectric constant is static at low frequency, the phenomenon results in separation of the dielectric constant into a complex dielectric constant at high frequency, as given by Equation 2.14:

$$\varepsilon = \varepsilon' - j\varepsilon'', \tag{2.14}$$

where $\varepsilon'$ is the real part of this equation, which is the same as the static dielectric constant, and $\varepsilon''$ is the imaginary part of this equation representing the losses.

In general, the loss effect is characterized by the loss tangent, which is the ratio of the imaginary part to the real part, as given by Equation 2.15:

$$\tan\theta = \frac{\varepsilon''}{\varepsilon'} \cong \frac{\sigma}{\omega\varepsilon'}, \tag{2.15}$$

where $\sigma$ is conductivity of the dielectric material and $\omega$ is angular frequency in radians per second. The loss tangent is one of the measures of the dielectric material to evaluate the properties at high frequency. As shown in Figure 2.6, FR4 has a higher, more uneven loss tangent at high frequency as compared with other more expensive dielectric materials [8]. Therefore, electrical design engineers should take into account the loss tangent when designing the high-frequency interconnects on FR4 board.

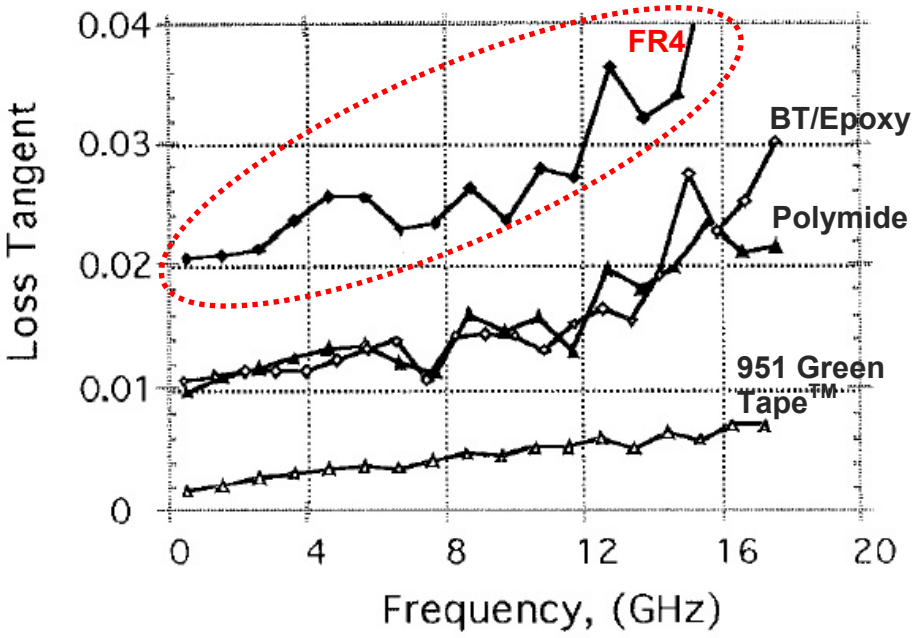



Figure 2.6. Loss tangents of different dielectric materials [8].

### 2.4.1.3. Manufacturing variations in the dielectric constant

The dielectric constant of substrate materials considerably affects the signal transmission characteristics of high-frequency interconnections. In particular, two important characteristics, the characteristic impedance and the propagation velocity, directly depend on the dielectric constant. One of the factors affecting the dielectric constant is the composite ratio of material components. FR4, which is commonly used in commercial digital applications, consists of an epoxy matrix reinforced by a woven glass cloth. The glass-to-resin ratio of FR4 is approximately calculated by Equation 2.16 [28]:

$$\varepsilon_r \cong \varepsilon_{rsn} V_{rsn} + \varepsilon_{gls} V_{gls}\,, \tag{2.16}$$

where $\varepsilon_{rsn}$ and $\varepsilon_{gls}$ are the dielectric constants of the resin and glass, respectively, and $V_{rsn}$ and $V_{gls}$ are the volume fractions of the resin and glass, respectively.

In particular, the glass-to-resin ratio of each FR4 sample, when it is manufactured, is not consistent because of the manufacturing tolerance, which hinders the yield performance. Therefore, variations in the dielectric constant should be considered to achieve a robust digital design; manufacturing inconsistency is one of the reasons that the measurement-based techniques and statistical approaches are suggested in many practical applications.

#### 2.4.1.4. Conductor surface roughness

At high frequency, the skin effect moves the current to the surface region, the thickness of which is defined as skin depth. The skin depth formula mentioned in Equation 2.13 is derived under the assumption that conductor surface is perfectly level. In the real world, however, the conductor surface is so rough that it affects signal integrity [29]. Moreover, the conductor surface roughness is too random to predict its effects in the skin depth. Figure 2.7, captured by a scanning electron microscope (SEM), shows the random surface roughness on a FR4 board.

Generally, the surface variation is characterized by the tooth size of the conductor surface [6, 29]. When the skin depth, varying with increases in frequency, reaches the tooth size, the skin depth formula loses its predictability for the high-frequency

interconnect design. Thus, electrical engineers have to manage carefully the conductor surface roughness in their designing and manufacturing steps.

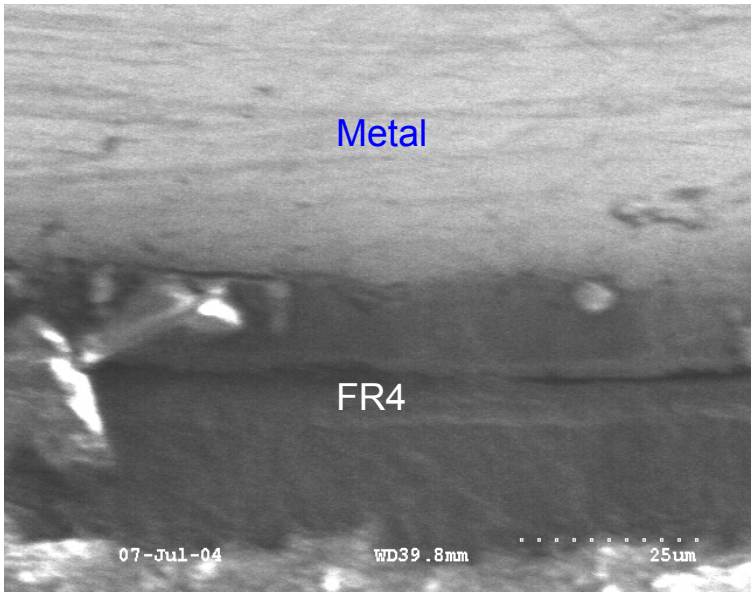



Figure 2.7. Photomicrograph of FR4 surface roughness.

### 2.4.2. Geometrical limitations

When electrical engineers draw the interconnect paths on the board, an interconnection does not consist of only a single short straight line. Accordingly, traces that are routed in various interconnect structures are used to meet the requirements of board aspect ratios, timing, and area limitation. These structures involve long traces, couplings and geometrical discontinuities such as vias and bending structures.

If they are not co-designed properly with the compatible models, then, the system performance can be unintentionally degraded and may then not guarantee full system performance. Furthermore, large-size structures, which are generally used on the board,

need to be considered carefully with the compatible models because their signal integrity is so sensitive to choice of a structure that a careful design process with a proper model should be taken. The following subsections show the significance of considering geometrical limitation by the empirical examples containing geometrical limitations.

#### 2.4.2.1. Long straight line of different dielectric materials

A transmission line fundamentally can be expressed by lumped RLC elements that directly depend on line length and frequency. Generally, a model of a high-frequency transmission line needs many lumped RLC elements resulting in much loss. Consequently, line length of high-frequency interconnect is a significant factor for signal integrity especially on low-cost material such as FR4.

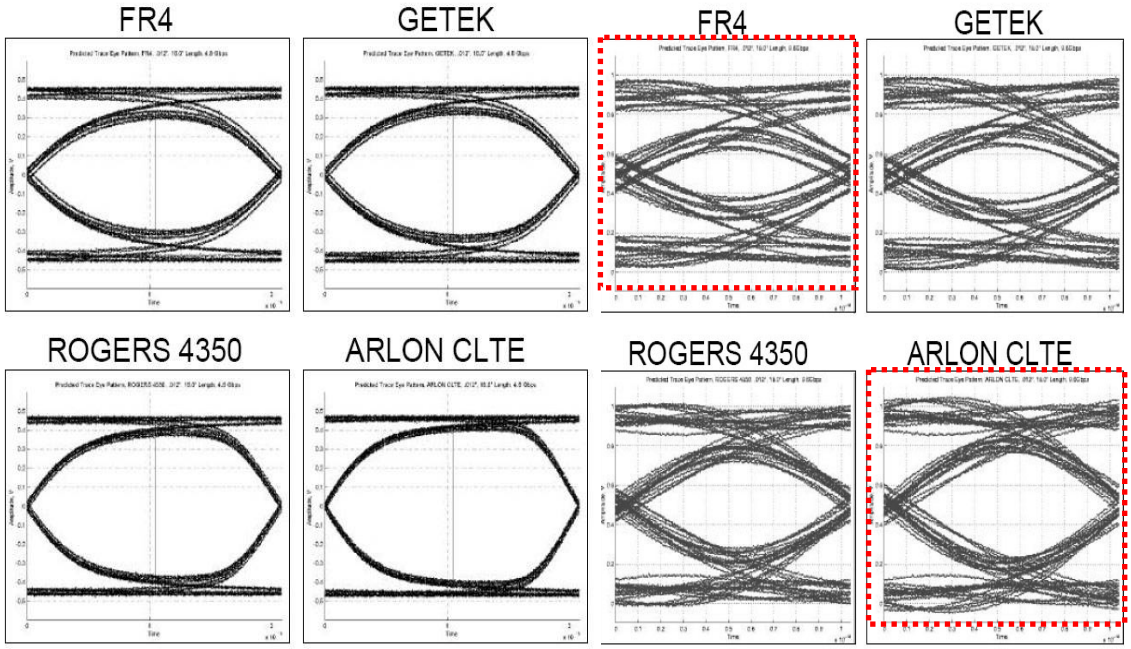
Table 2.1 shows characteristics of different board materials in terms of electrical properties and relative cost (this cost factor is derived from 10-inch by 12-inch, 12-layer backplane) [7]. In this table, it is indicated that FR4 and GETEK are more cost-effective

Table 2.1. Properties of different board material [7].

| Material | ε r @1 MHz | E r @1 GHz | tanδ @1GHz | Relative Cost |
|---|---|---|---|---|
| FR4 | 4.30 | 4.05 | 0.020 | 1 |
| GETEK | 4.15 | 4.00 | 0.015 | 1.1 |
| ROGERS 4350/4320 | 3.75 | 3.60 | 0.009 | 2.1 |
| ARLON CLTE | 3.15 | 3.05 | 0.004 | 6.8 |

but have more loss than the other advanced materials. With these board materials, Figure 2.8 shows eye diagrams at 5 Gbps and 10 Gbps, which results from a 1-volt, 32-bit inverting K28.25 input bit pattern. The test structures are 18-inch, 12-mil wide stripline traces that are 50-Ω characteristic impedance [7].

These results show that although all four materials have decent eyes at 5 Gbps the low-cost materials, FR4 and GETEK, are not acceptable at 10 Gbps and only the two advanced materials, ROGERS 4350 and ARLON CLTE, have acceptable eyes at 10 Gbps. It is inferred that a low-cost material should be designed with an accurate model especially in long trace configuration and at high frequency to meet signal integrity.




(a) 5 Gbps (b) 10 Gbps

Figure 2.8. Eye diagrams of different board materials [7].

### 2.4.2.2. Long straight lines with vias

In order to miniaturize board designs designers would like to use vertical as well as horizontal interconnect architectures such as multilayer board construction. Thus, connections between layers become crucial, however, this it results in geometrical discontinuity that severely limits performance. Among these connections, a via, a hole drilled through layers serving connection elements in multi-layer printed circuit board (PCB), is prevalent and versatile. It thus is important to observe the effect of incorporating a via in an interconnection system.

Herein, the transmission lines of different lengths on an FR4 board are designed and measured at different lengths and frequencies. 1- , 10- and 20- cm long transmission lines that are 130-mil wide for 50-Ω impedance matching are fabricated on the FR4 board having a relative dielectric constant of 4.3. All transmission lines are conventional microstrip lines, and the via size is specified to be the minimum fabricating capability of 20 mils as shown in Figure 2.9. The transmission lines with vias are connected from the top layer through the via path to the bottom layer on the two-layer structure.

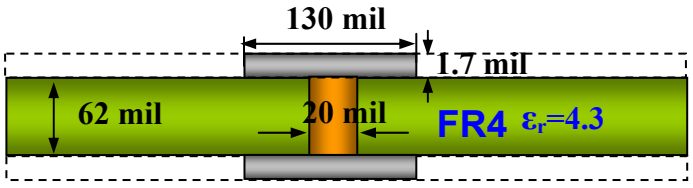
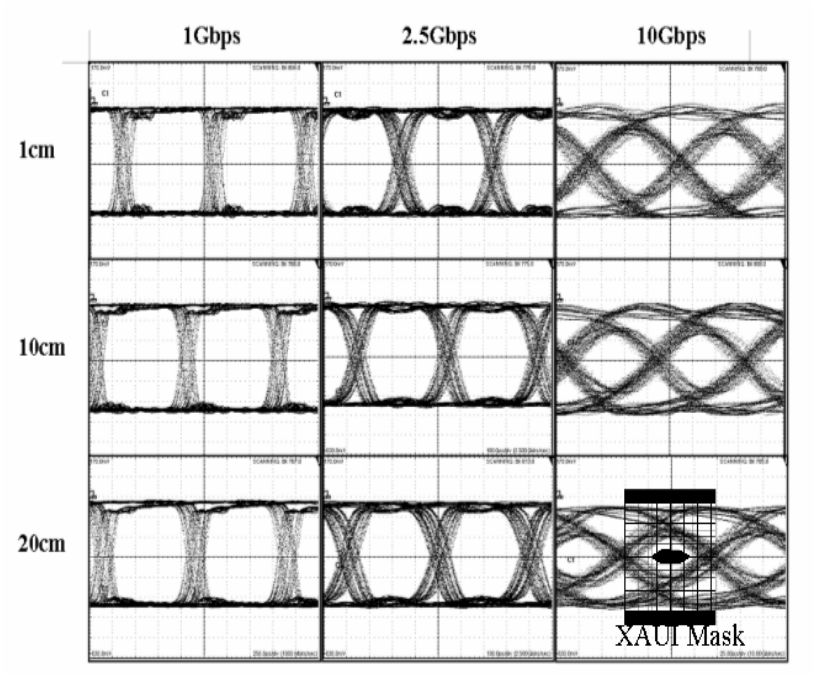
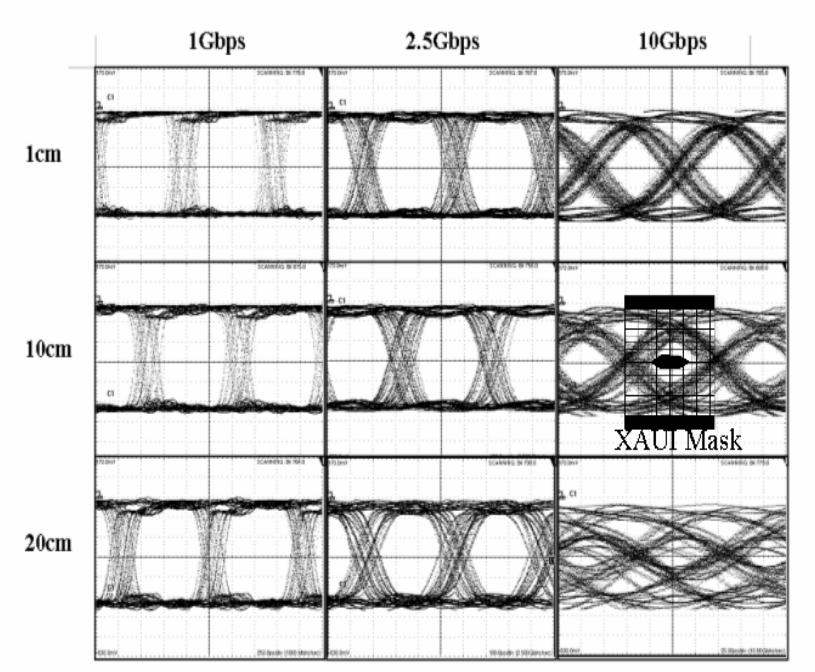



Figure 2.9. Cross-section view of a transmission line with a via.




(a) Transmission line without a via




(b) Transmission line with a via

Figure 2.10. Measured eye diagrams of transmission lines.

Eye diagrams for 1- , 2.5- and 10- Gbps data rates produced from $2^7$-1 pseudo random bits (PRBs) input patterns were obtained for different lengths using a digital oscilloscope and a pattern generator. As to the measurement configuration, all transmission line measurements are performed with termination to reduce the reflection loss. As shown in Figure 2.10, vias have critical effects on data transmission according to the eye patterns. The eye on the 20-cm long transmission line with a via is almost closed at 10 Gbps compared to one without vias. The results indicate that a via is an essential element for connecting layers but has a considerable impact on the signal integrity. Therefore, the effect resulting from incorporating a via on the board, which may be ignored at low frequencies, should be taken into account at high frequencies.

#### 2.4.2.3. Structures with couplings and bends

Electrical designers handling high-frequency interconnects have to strive to avoid the geometrical discontinuities because the geometrical discontinuities have a substantial influence on performance of interconnects on the board at high frequency. In reality, however, coupling and bending structures will inevitably be utilized for routing as will vias.

Coupling is represented by two mechanisms, mutual inductance and mutual capacitance. Magnetic fields from a driven line induce current onto a victim line, which represents mutual inductance. This mutual inductance generates voltage noise in the victim line by the simple equation [6]:

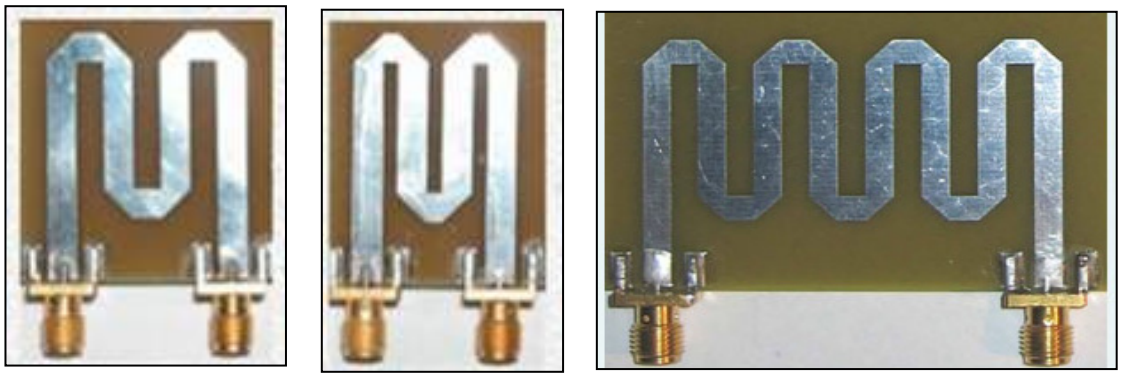
$$V_{Lm} = L_m \frac{dI_{driver}}{dt}. \quad (2.17)$$

On the other hand, mutual capacitance results from coupling of an electric field between two conductors, which produces a current noise onto a victim line by the simple equation [6]:

$$I_{Cm} = C_m \frac{dV_{driver}}{dt}. \quad (2.18)$$

As to bending structures, right-angle bend is usually used because of its simplicity, although countless degrees of bend are possible to route paths. In simple equivalent circuits, this structure contains capacitance arising through charge accumulation at the outer corner and inductance arising from current flow interruption in the outer edges (where most current flows). To compensate for the discontinuity, some attempts with curved bends and mitred bends have been made in designing interconnects.

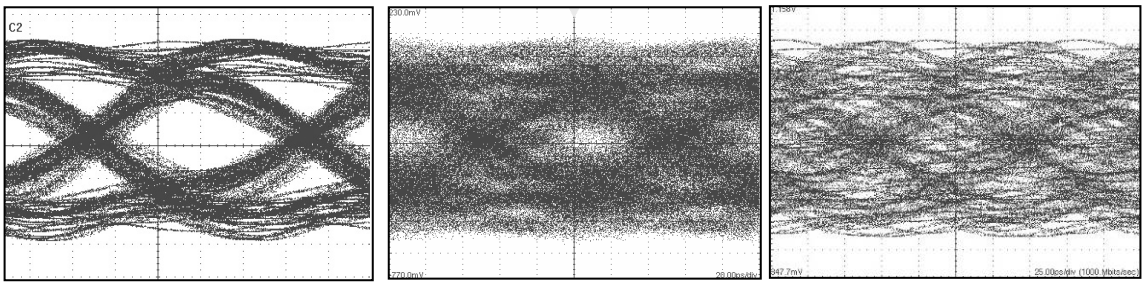
A serpentine structure is a good candidate to see the discontinuity effects because it contains the coupling and bending structures. Figure 2.11 (a) shows a 3-turn, 130-mil wide serpentine structure, and Figure 2.11 (b) shows a structure with half spacing of Figure 2.11 (a) to see coupling effects. Additionally, Figure 2.11 (c) shows a structure containing more bending structures than Figure 2.11 (a) does.



(a) (b) (c)

Figure 2.11. Test structures of 130-mil wide serpentine structures with: (a) 3-turn and 130–mil spacing, (b) 3-turn and 65-mil spacing and (c) 7-turn and 130-mil spacing.

With these test structures, eye diagrams are obtained at 10 Gbps from $2^7$-1 PRBs input patterns to see what degree of coupling or bending discontinuity degrades signal integrity. Figure 2.12 (a) and (b) show the contrastive eye diagrams with respect to different spacing, which show coupling effects. Assuming that the bending effect is dominant over straight line in these test structures, Figure 2.12 (a) and (c) also show the contrastive eye diagrams which demonstrate the bending effects.



(a) (b) (c)

Figure 2.12. Measured eye diagrams of 130-mil wide serpentine structures with: (a) 3-turn and 130-mil spacing, (b) 3-turn and 65-mil spacing and (c) 7-turn and 130-mil spacing.

Therefore, these results indicate that ill considered design of structures with geometrical discontinuities can degrade signal integrity; we may infer necessity of the better modeling for optimization of the system.

## 2.5. Modeling Methodology

Modeling methodologies for interconnects have been approached in different ways in two different technical areas, microwave engineering and digital engineering. Digital engineering has focused on the timing analysis at somewhat low frequencies. On the other hand, microwave engineering has researched the modeling of the transmission lines to meet the design specifications in the narrow high-frequency range. As the frequency of a digital signal increases, these two technical areas have converged to develop the modeling of high-frequency interconnects. Accordingly, high-frequency digital interconnects adopt the frequency analysis based on the resourceful electromagnetic equations, numerical computation and measurement techniques [47-51]. In this section, three different basic modeling approaches are introduced briefly to understand the proposed method.

### 2.5.1. Analytical equation-based approaches

Electromagnetic theory has been well established over the past 100 years by many researchers. Maxwell's equations are fundamental for the transmission line modeling. Based on Maxwell's equations, a transmission line in a TEM configuration can be

expressed as the distributed RLGC model, which is composed of resistance per unit length, inductance per unit length, conductance per unit length and capacitance per unit length [6]. The analytical equation method is one way to find an analytical model using equations derived from the fundamental Maxwell's equations for appropriate transmission line structures. The pure analytic model, however, does not follow the behavior of the transmission line in the real world as the structures that yield analytical solutions to Maxwell's equations a few and inadequate for most design work. Practically, except for the simple structure such as a single straight line, it is very difficult to derive the analytic model from the principal equations without numerical methods or approximations or both.

Although the analytical equation method is not quite practical, it provides an intuitive guide and theoretical background for the two following methods. There are some techniques, such as conformal mapping [30], and measurement enhanced models that extend the generic analytical methods for practical designs, however this generally results in an inflexible nonscalable design tool not the predictive tool described here.

### 2.5.2 Numerical electromagnetic full-wave-based approaches

The numerical full-wave method is a very flexible method that microwave engineers frequently use for their designs and simulations. This method divides geometrically arbitrary structures into small segments to analyze the electromagnetic responses. The responses of each segment are computed to obtain the responses of the entire structure using various numerical methods. The simulation time of the numerical

full-wave method depends on the number of segments and frequency points. Consequently, geometrically complex structures containing a number of discontinuities require a long time to simulate using this method. In addition, non-ideal effects such as statistical variation or surface roughness are not easily taken into consideration in this process.

Among the numerical full-wave electromagnetic methods, the finite difference time domain (FDTD) method [31-33], the finite element method (FEM) [31, 34], the method of moments (MoM) [35-37] and the partial element equivalent circuit (PEEC) method [38-46] are popular approaches used in various simulation tools. The FDTD method and the FEM are derived from differential forms of Maxwell's equations. These differential equation-based methods discretize the entire area and treat the local coupling among the finite cell of whole grid area. Accordingly, the differential equation-based methods have larger, but sparse, interaction matrices. On the other hand, the MoM and the PEEC method are derived from integral forms of Maxwell's equations. These integral equation-based methods make only conducting path discretized and consider the global coupling. Hence, integral equation-based methods have the small, dense interaction matrices.

In this thesis work, the equivalent circuits used in the PEEC method are modified for the proposed measurement-based modeling method. In addition, a common simulation tool based on the MoM is compared to the proposed method to clarify advantages of this thesis work.

### 2.5.3. Measurement-based approaches

Designs that successfully meet the specifications in simulations should prove their performance compared with measured data. Consequently, the measurement-based method is very accurate because measured data are the final goal to the modeling and the model produced by this method includes empirically non-ideal effects such as the manufacturing variations and the frequency dependent variables.

In general, the time domain reflectometry (TDR) and the vector network analyzer (VNA) are commonly used for this measurement-based modeling. A TDR measures the reflected responses for a short period pulse and characterizes the characteristic impedance and the propagation velocity based on the shapes of the responses such as peaks, valleys, oscillations and relaxations [6]. On the other hand, a VNA is designed to measure the frequency responses of the device under test (DUT). Its primary output is the scattering matrix (S-parameter) representing the information about the reflected signal ratio and transmitted signal ratio [10]. The S-parameter data are informative to consider the frequency dependent variables on the model at high frequency.

The measurement-based PEEC method using the S-parameter data offer a good approach to obtaining the rapid, predictive model [50, 51]. The PEEC method provides an equivalent circuit compatible with the circuit simulation tools and the parameters of the equivalent circuits are curve-fitted to the measured S-parameter data. Finally, the blocks of the equivalent circuits are recomposed to predict the other structures containing the small components.

# CHAPTER III

## PREDICTIVE MEASUREMENT-BASED PEEC MODEL METHODOLOGY

### 3.1. Introduction

This chapter describes the predictive measurement-based PEEC modeling method that can be applied to the high-frequency interconnect on FR4 board. A general measurement-based method, the measurement based PEEC method is potentially very useful for high-frequency interconnect modeling because non-ideal effects that have significant impacts on signal integrity such as frequency dependent variables and manufacturing variation can be automatically included in the models. We consider these effects by optimizing equivalent circuit parameters (we call these parameters EC-parameters to avoid confusion with Z-parameter or S-parameter) using measured S-parameter data that represent frequency response of the interconnects. This method naturally incorporates the non-ideal effects although we do not intentionally force the circuit elements to represent these effects.

Since the PEEC model is suitable for a building block representation for scalability [50, 51], it is a good choice for predictive modeling. The EC-parameters of the PEEC model are optimized by using standard simulation tools and then used to extend the PEEC model to enhance the flexibility of the model by prediction. The electrical performance comparison of the results from the predictive model with measurements demonstrates the usefulness of the described method. Hence, the predictive models compatible with the circuit simulators may provide powerful ways of co-design and co-

simulation with circuitry. In this chapter, the methodology procedure is briefly described, and an explanation of the steps selected, at length, is provided in subsequent sections.

### 3.2. Modeling Procedure

The proposed modeling procedure can be depicted by a flow chart as shown in Figure 3.1. The modeling procedure consists of two parts: initial modeling and generalization. The initial modeling part includes several steps to develop a predictive model, and the generalization part extends the predictive model.

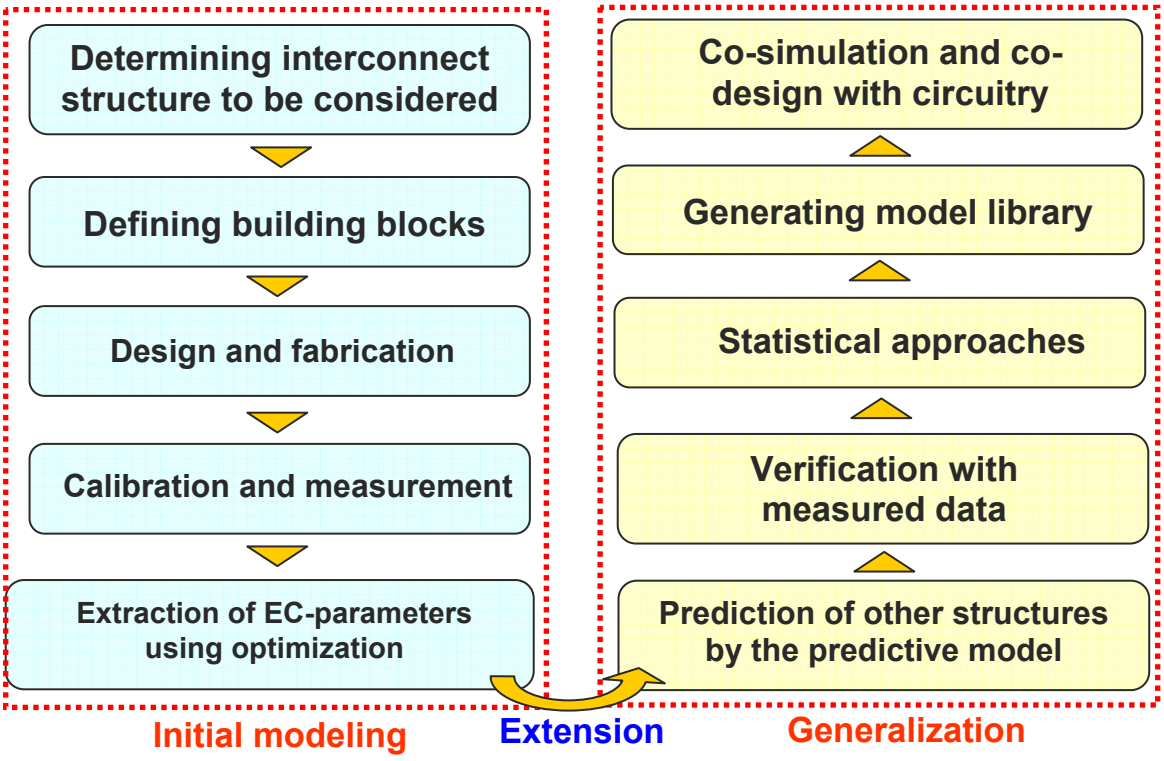



Figure 3.1. Flow chart of procedure of the predictive measurement-based PEEC modeling method.

### 3.2.1. Initial modeling

Interconnect structures interesting to the electrical designers usually contain small building blocks representing the physical segments. Accordingly, defining building blocks for the interconnect structures is important in predictive modeling. The interconnect structures for the predictive model are designed using a commercially customized CAD tool and fabricated according to its design rules. The S-parameter data for modeling and verification in the frequency domain are measured by a VNA, and eye diagrams are measured for verification in the time domain by a pattern generator and a digital oscilloscope. The measured S-parameter data are converted to impedance parameter (Z-parameter) data to find the initial value for EC-parameters and to be used in our optimization process.

Equivalent circuits for simple structures may be relatively easy to determine by the fundamental electromagnetic (EM) equations. However, it is difficult to determine equivalent circuits of complex structures in a similar way since these equivalent circuit parameter equations are highly nonlinear. For this reason, we find equivalent circuits that are intuitively modified from the basic PEEC model in such a way that the equivalent circuit can take into account the geometry of a given structure. This alleviates our difficulty in determining the equivalent circuits. The PEEC model with multiple building blocks is very informative for representing the behaviors of the Z-parameter data since the high-order polynomial equations of the Z-parameter data containing a number of coefficients have sufficient nonlinearity as in Equation 3.1: (Note that a simple linear equation may not follow the nonlinearity of the Z-parameter data.)

$$Z_{ij}(V,\omega) = \frac{a(V,\omega)}{b(V,\omega)} \approx \sum_{k=0}^{n} q_k \omega^k \quad , \tag{3.1}$$

where $\omega$ and $Z_{ij}(\omega)$ represent frequency in radians per second and Z-parameter data converted from measured S-parameter data respectively, both a and b represent polynomial functions whose coefficients are combinations of various circuit parameter values, and V and $q_k$ represent a parameter set of RLC equivalent circuit and approximated coefficients respectively.

Finding initial values for optimization is a key to achieving the optimum. When the equivalent circuits of the interconnect structure have the Z-parameter data with a resonant point, the initial values can be obtained readily by calculating those Z-parameter data. On the contrary, when a more complicated structure, where Z-parameter data have several resonant points, is concerned, it may be too difficult to find directly the initial values in a similar manner. To avoid this difficulty, we divide the complicated structure into several, simple test structures to apply the method for finding the initial value for a simple structure. With the initial values, relatively accurate EC-parameters of the predictive model are determined by three optimization methods in the ADS simulation tool: Random, Gradient, and Minimax [53]. More detailed explanation is provided in Section 3.5.

### 3.2.2. Generalization

Once the optimized equivalent circuits are obtained, a combination of the equivalent circuits, a predicted structure, demonstrates the usefulness of the predictive

model. Comparison of the predicted structure with the measured data both in frequency domain and in time domain is required to verify the modeling accuracy. More concretely, Z-parameter data simulated with the predicted model are compared and analyzed with the measured Z-parameter data of the same structure. The simulated eye diagrams of the predicted structure verify the prediction performance in time domain in comparison with those of measured data. Although the measured data of one structure are reliable most of the time, we need to confirm that a different piece of the same structure can generate the same measured data and that the exact same piece can generate the same data repeatedly. Therefore, the statistical approaches are required for obtaining models that are more reliable.

With all results from prediction and statistical approaches, a design library of the structures interesting to designer can be established for co-design and co-simulation. Since the library generates RLC equivalent circuit compatible with the common simulators, it is efficient and easy for co-design and co-simulation unlike numerical full-wave method tools that suffer from heavy computational loads.

## 3.3. Partial Element Equivalent Circuit (PEEC) Model

The PEEC approach has prevailingly been used to model high-frequency interconnects with numerical techniques until now [38-46]. The PEEC model is derived from electrical field integral equation (EFIE) to represent electrical behavior of physical geometry. The PEEC model has three main advantages. It is compatible with most circuit simulators, thus achieving simulation without additional processes. It also can facilitate

equally both time and frequency domain simulations; moreover, its elements easily interpret physical reality. In this section, we describe a brief derivation of the PEEC model for simple structure from the integral equation, which will be used for the basic PEEC model in the following chapter.

The unknowns of integral equation are the charges on the conductor surface and the current density within the conductors. Since the unknowns are defined by only the conductor, integral equation-based approaches are more efficient for interconnects with large free space than differential equation-based approaches. Assuming that time retardation is ignored and partial element of PEEC is definite, the integral equation can be derived from the summation of electrical fields in a conductor [38, 39, 42]. Here, we consider only rectilinear topology where the entire current only propagates in a parallel direction to the axes.

The relationship with the vector potential ($A$) and scalar potential ($\Phi$) can be expressed in an equation [38, 39] as

$$E(x,t) + \frac{\partial A(x,t)}{\partial t} \equiv -\nabla\Phi(x,t)\,. \tag{3.2}$$

Since the current propagates in the conductor, electric field ($E$) and current density (J) obey Ohm's law as

$$E(x,t) \equiv -\frac{1}{\sigma} J(x,t)\,, \tag{3.3}$$

where $\sigma$ is the conductivity of the conductor. By substituting Equation 3.2 with Equation 3.3, we can establish the EFIE as given by Equation 3.4:

$$\frac{J(x,t)}{\sigma}+\frac{\partial A(x,t)}{\partial t}+\nabla\Phi(x,t)=0\,, \tag{3.4}$$

where the first term represents the resistive elements of the conductor, the second term represents the inductive elements and the third term represents the capacitive elements.

Now, we consider the rectangular structure to be used for the basic shape in this thesis work as shown in Figure 3.2. This structure has the two inductive cells $S_2$ and $S_4$ and the three capacitive cells $S_1$, $S_3$ and $S_5$. Assume that $S_1$, $S_3$, and $S_5$ cells are characterized by potential $\Phi_1$ and charge $q_1$, $\Phi_3$ and $q_3$, and $\Phi_5$ and $q_5$, respectively. As to the inductive cells, $S_2$ and $S_4$ are characterized by the currents $i_2$ and $i_4$, respectively [38, 39].

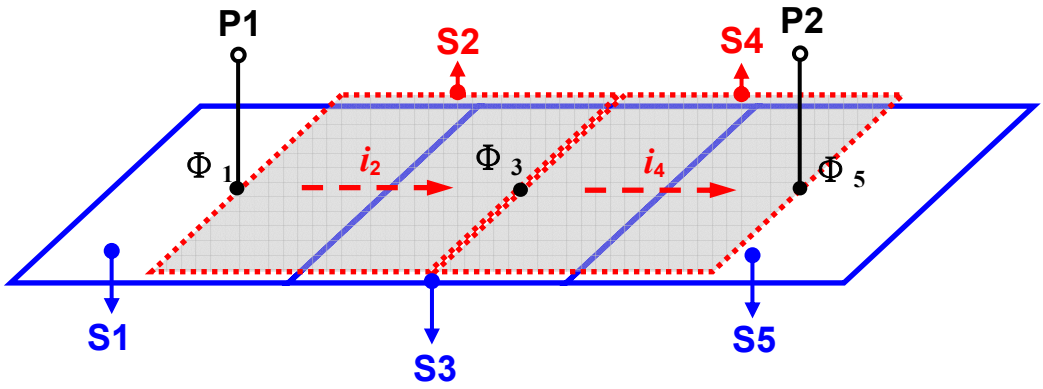



Figure 3.2. Rectangular structure divided into two inductive and three capacitive cells.

Using these characterization and the surface integrations of each term in the EFIE according to each cell, we can interpret the resistive, inductive and capacitive effects among each cell as the equivalent circuit as shown in Figure 3.3. More detailed description of the derivation is provided in [38, 39, 42]. This equivalent circuit will be

modified to be used for the equivalent circuits of the rectangular building block in this modeling work.

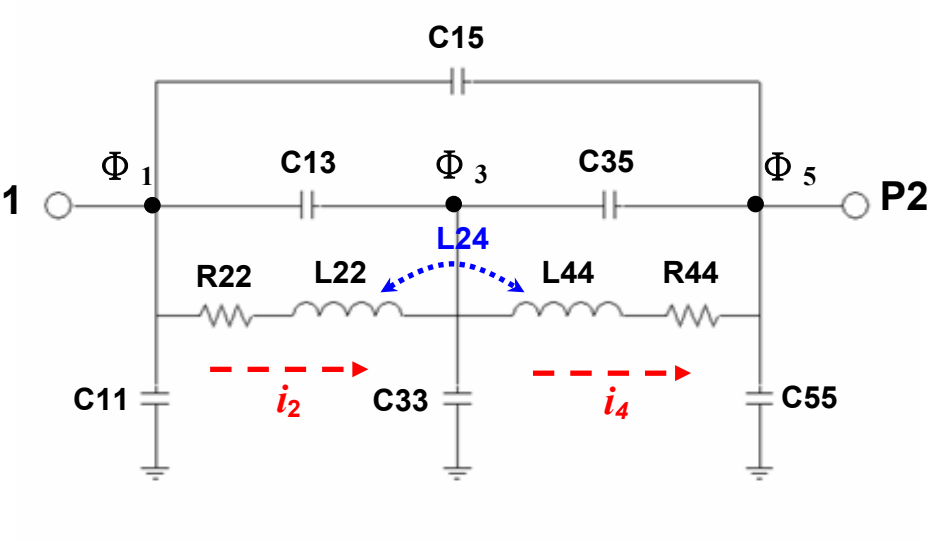



Figure 3.3. Basic PEEC model of the rectangular structure.

### 3.4. Measurement

Designs meeting successfully the specification in simulation should prove their performance in the real world using measurement techniques. Furthermore, if electrical engineers adopt the methodology based on the measurement data, it is very important to use the accurately measured data using proper equipment and techniques. In this thesis work, we use two different measurement setups: frequency-response measurement setup with a VNA and time-response measurement setup with a pattern generator and a digital oscilloscope.

Since the Hewlett-Packard Company developed the vector network analyzer (VNA) in the late 1960s, the VNA has served as the main piece of equipment used for accurate high-frequency domain measurement in microwave engineering [10, 57]. As the

frequency of digital signals has increased, the VNA has now become a suitable technique to consider frequency dependent terms in digital engineering. A VNA is designed to measure the frequency response of a DUT. Its primary output is S-parameter matrix representing the reflected and transmitted signal ratios. The S-parameter data are sufficient to model the behaviors of the high-frequency interconnect. Figure 3.4 shows the frequency-response measurement setup with VNA. A DUT is placed on the fixture customized for geometrical stability and electrical isolation. Prior to the measurement, calibration is performed using a 3.5 mm SMA connector calibration kit to remove all the effects except for the test structures.

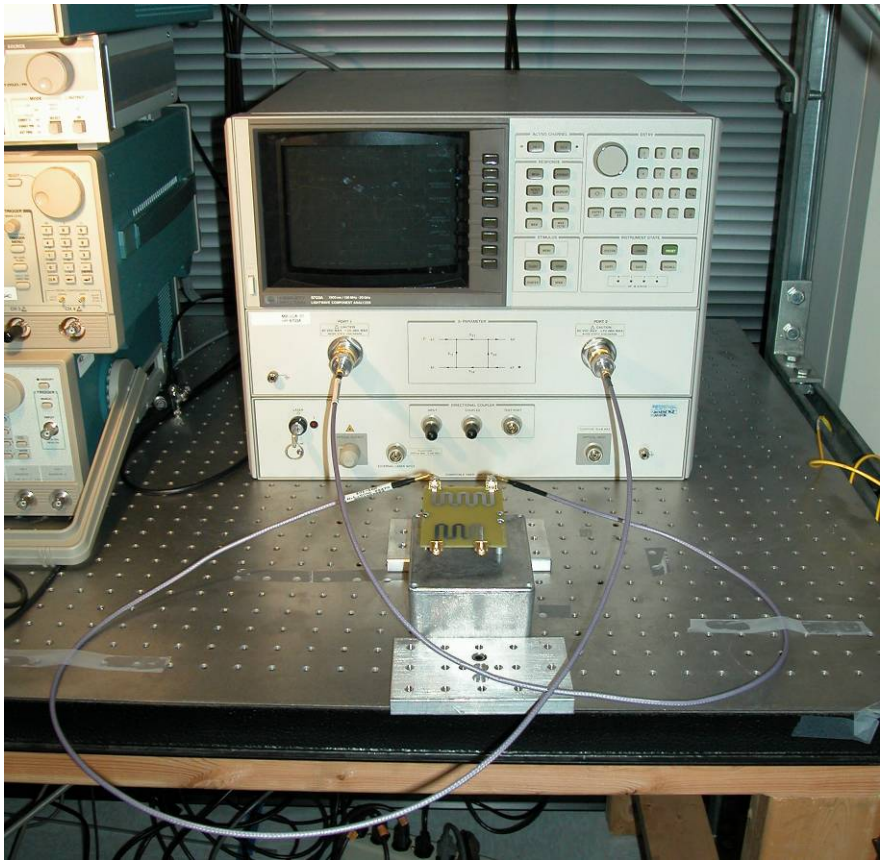
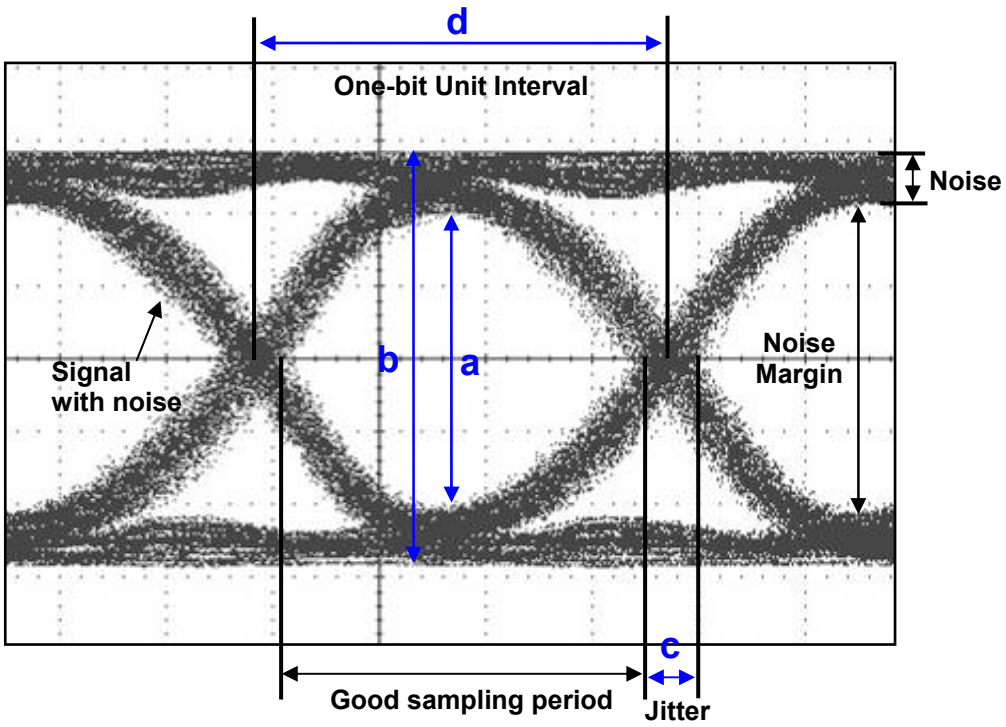


Figure 3.4. Frequency-response measurement setup.

As for time domain measurement, in digital communication, an eye diagram contain important information such as noise, noise margin, and jitter in its pattern as shown in Figure 3.5. Noise is recognized by the thickness of the top and bottom line of eye pattern. Noise margin is interpreted by the eye opening in the center of a pulse period. Jitter is the crossing width at the intersection between each eye pattern and refers to the ambiguity of pulse timing [54, 56, 58].




* Eye-opening: $\frac{a}{b}\times 100\%$ *Jitter: $\frac{c}{d}\times 100\%$ [UI]

Figure 3.5. Measured eye pattern.

To obtain the eye diagram, we build up the measurement setup with a pattern generator and a digital oscilloscope as shown in Figure 3.6. The input pattern is $2^7$-1 PRB pattern to emulate the communication environment used for Ethernet networks.

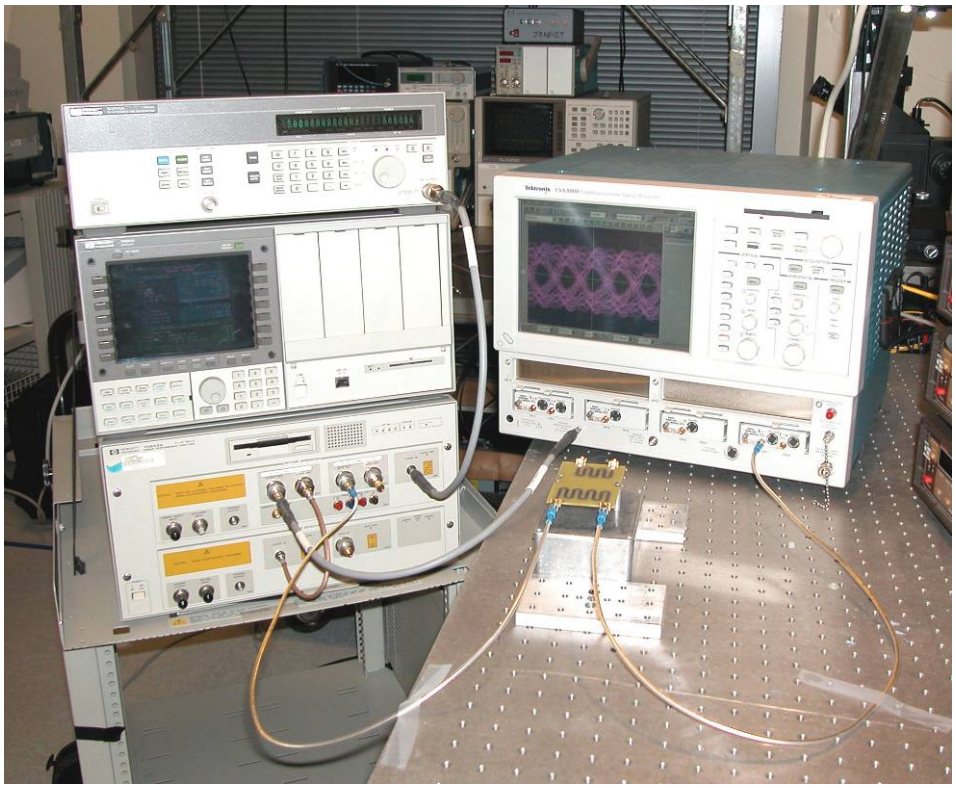


Figure 3.6. Time-response measurement setup.

## 3.5. Optimization Methods

Optimization is essential in device modeling and design. Various optimization methods have been used in many research problems, but their usefulness may depend on the characteristics of problems [52, 53]. In this section, we describe three optimizers used in this work: the random, gradient and minimax optimizers built-in the ADS simulation

tool [53]. These optimizers are classified based on which search method and error function are used for optimization. The search methods are used to determine a new set of parameters closer to a desired set of parameters. The error functions can be variously defined. As shown in Table 3.1, the optimizers use various search methods. Regarding the error function formulations, both the random and the gradient optimizers use the least-squares error function, and the minimax optimizer uses the minimax error function. Herein, the three search methods are summarized, and the two error functions are briefly explained.

Table 3.1. Types of optimization.

| Optimizer | Search method | Error function formulation |
|---|---|---|
| Random | Random search | Least-squares |
| Gradient | Gradient search | Least-squares |
| Minimax | Gauss-Newton/<br>Quasi-Newton search | Minimax |

The random search is typically used for the initial stage. It starts with a set of initial parameters; a user enters the initial parameters and the search range for each parameter. After the first trial, the next set of the parameters is determined by perturbing these initial values within the search range of each parameter using a random-number generator. The value of a given error function evaluated at the initial set of the parameters is compared with the two values of the error function evaluated at the set of parameters

obtained by negative and positive perturbations of each parameter to decide the next set of parameters.

The gradient search is generally applied when the initial set of parameters is located "near" the target minimum. This method finds a direction for the search to change the parameters by computing the gradient of a given error functions. The parameters are changed in the direction to minimize the error function, and then a new gradient is evaluated for the next iteration.

The Gauss-Newton/Quasi-Newton search method is used in the minimax optimizer consisting of two stages. In the first stage, a linear programming technique is used to solve a minimax problem. In the second stage, a Quasi-Newton method is used to determine a direction for the search to minimize the error function using a second-order derivative approximation of the error function.

The random optimizer and the gradient optimizer use the least square error functions. In a least-squares error function, the differences between the desired frequency response and the current frequency response are squared and then averaged over frequency. This may be written by [53]

$$E = \sum_{j} \frac{\left[ \sum_{f} \sum_{i} W_{ij} \bullet \left| R_{ij}(f) - G_{ij} \right|^2 \right]}{N_j}, \tag{3.5}$$

where $R_{ij}(f)$ and $G_{ij}$ are the current frequency response and the goal response associated with the indices $i$ and $j$, respectively, and $N_j$ and $W_{ij}$, represent the number of frequencies in the $j$-th frequency range and the weighting factor, respectively.

The minimax error function defines an error as the maximum value over all the errors evaluated at all frequency points, which are well-defined. The minimax optimization is performed by minimizing this maximum value, which explains why such an optimization is called the "minimax" method. Namely, the error is defined as the maximum difference between the desired frequency response and the current frequency response. The mathematical formulation is given by

$$U = Max_i(E_i), \tag{3.6}$$

where $U$ represents the error function, and $E_i$ is a difference (or an error) between the desired frequency response and the current frequency response evaluated at the $i$-th frequency point. Then, the error function $U$ is minimized to find a set of optimized results; since $U$ represents the possible "worst case," the relevant analysis is often called the "worst case" analysis.

## 3.6. Performance Evaluation

As many models exist in various areas, methods of model evaluation have been used diversely. In general, there are three main attributes in computational modeling: accuracy, efficiency and utility [52, 55]. Since the method suggested here needs to be compared with a computational method, we consider these attributes to evaluate it with the momentum simulation which is defined as the simulation by the ADS momentum simulation tool in this dissertation. Among the attributes, accuracy is the most important because it is a functional requirement. Accuracy is a quantitative degree with which we

determine whether the model agrees with the real response. Efficiency is the relative cost to develop the model, and utility is the applicability to modeling work.

In this thesis, accuracy is evaluated in the frequency and time domains. Since the desired responses are measured data, in the frequency domain, Z-parameter data of the prediction are compared with that of measured data and the momentum simulation. In the same manner, predicted eye diagrams are evaluated with measured eye diagram and eye diagram converted from frequency data. As to efficiency, although it widely includes computational cost and human cost, herein, we take into account simulation times in the same computer resource. Utility is a somewhat subjective attribute in comparisons of different approaches. In the sense of accessibility to resource, because VNA is so prevalent and easily accessed in the modeling arena, we assume that utility of both approaches is equally sound. In summary, evaluations for modeling entail three comparisons: Z-parameter comparison in the frequency domain, eye diagram comparison in the time domain and simulation time.

# CHAPTER IV

## MODELING OF STRAIGHT MICROSTRIP LINES

### 4.1. Introduction

As the problems of interconnects between systems on boards have gained a special concern in diverse groups, many attempts have been made to address these problems. One approach is co-design (co-optimization) with an accurate interconnect model in the design process. Generally, the simulation tools utilize the numerical full-wave methods to model the electrical property of the interconnects. As frequency required in a system increases, however, the simulation tools may not guarantee their usefulness in the sense of accuracy and efficiency. We can readily see this limitation, as the geometry of interconnects become more complex and data rates become higher. In particular, since interconnect on an FR4 board at 10 GHz is vulnerable to this limitation, it is a good candidate to motivate the proposed modeling method.

A microstrip line is a route used widely in digital systems because of its easy fabrication process. Although the straight microstrip line is basic and simple, it can suffer from poor signal integrity with long lines. In this chapter, to see how the modeling method works, straight microstrip lines with different line lengths are designed, measured and modeled. The electrical performance of the predictive model is verified based on measured response. With the established model, we evaluate the accuracy and efficiency of the predictive model with those of the ADS momentum simulation.

## 4.2. Modeling Description

### 4.2.1. Determination of building block

A decisive factor of model performance is the determination of building blocks. Building blocks are a basic section representing physical reality that will be duplicated to achieve design scalability. Accordingly, test structure to be modeled should be a reasonable combination of individual building block. In general, more building blocks provide more flexible design options and more accuracy, but the more building blocks the longer simulation it takes to extract them and the more complicated the final model configuration (but generally, more building blocks does not change the final model simulation time).

In this chapter, as a rule of thumb, piece of interconnect is divided into tenth of maximum wavelength pieces for building blocks, this is a good way to ensure that lumped element models of the building blocks are valid. In order to find the physical length of a tenth of wavelength on a microstrip line, we consider quasi-TEM configuration. The electromagnetic wave in the quasi-TEM configuration experiences the discontinuity of dielectric material. This experience is interpreted by effective dielectric constant. Effective dielectric constant ( $\varepsilon_{eff}$ ) can be expressed as [10, 11]

$$\varepsilon_{eff} = \left( \frac{\lambda_0}{\lambda_m} \right)^2 , \tag{4.1}$$

where $\lambda_0$ and $\lambda_m$ are the wavelength in free space and the wavelength on microstrip line, respectively. The wavelength in free space is

$$\lambda_0 = \frac{C}{F}, \tag{4.2}$$

where $C$ and $F$ are the speed of light and maximum frequency on microstrip line. Therefore, substituting Equation 4.2 into Equation 4.1, we obtain the wavelength on microstrip line as given by Equation 4.3:

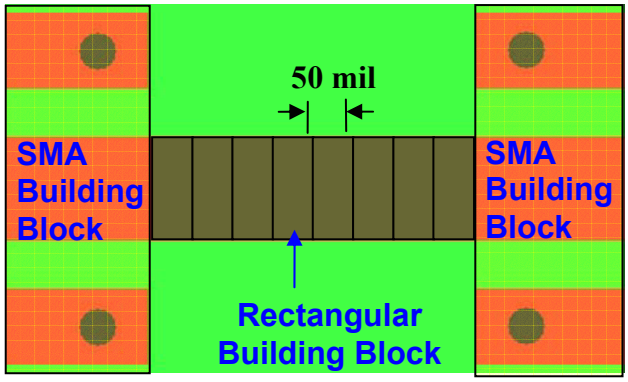
$$\lambda_m = \frac{300}{F\sqrt{\varepsilon_{eff}}}. \tag{4.3}$$

According to [11, 13], the effective dielectric constant is obtained as

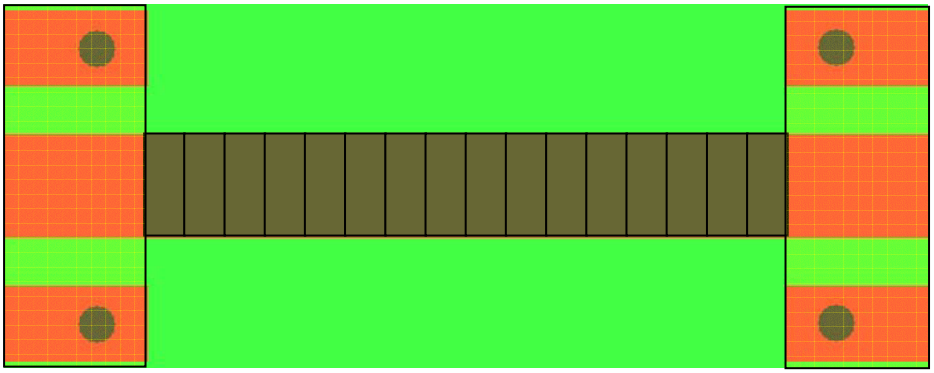
$$\varepsilon_{eff} = 1 + q(\varepsilon_r - 1), \tag{4.4}$$

where $\varepsilon_r$ is the relative dielectric constant and $q$ is the microstrip filling factor, which depends on ratio of width to height of a metal and is determined by the graph of [11, 13]. When calculated using Equations 4.3 and 4.4 with the specific values of the geometry and the material property used in this work, a tenth wavelength at 10 GHz is 64.61 mils. Therefore, the unit size of each building block is determined as a 50-mil long building block.

Figure 4.1 shows building block determination of a 400-mil long straight microstrip line, predictive structure and an 800-mil long straight microstrip line, predicted structure. These structures have the same kinds of building blocks for scalability. The 400-mil long line consists of two SMA connector building blocks and eight rectangular building blocks. The 800-mil long line has eight additional rectangular building blocks with the same building blocks as the 400-mil long line. Additionally, we can apply these building blocks for longer lines by adding building blocks.




(a) 400-mil long straight microstrip line



(b) 800-mil long straight microstrip line

Figure 4.1. Building block diagram of the straight microstrip lines.

### 4.2.2. Design and measurements

Test structures are designed with a low-cost double-sided FR4 board having 1.7-mil metal thickness and 62-mil thick dielectric material with a dielectric constant of 4.3. For efficient signal propagation, the width of the straight microstrip lines is calculated to have a 50-Ω characteristic impedance at 10 GHz in two different ways, one by the ADS Lincal simulator and the other by Equation 2.2 in Section 2.3.1. This equation is

evaluated at the specific values in the fabrication except for the line width, *W*, and is rearranged as

$$\left[\frac{W}{62}+1.393+0.667\ln\left(\frac{W}{62}+1.444\right)\right]^2\times\left[2.75+1.75\sqrt{\frac{W}{W+744}}-1.6398\frac{1}{\sqrt{W}}\right]=56.77\,. \qquad (4.5)$$

130-mil and 122-mil are the values of the line width calculated by the ADS Lincal simulator and Equation 4.5, respectively. In this chapter, hence, we designed 130-mil wide straight lines with five different line lengths: 400 mils, 800 mils, 1200 mils, 1600 mils and 2400 mils. Figure 4.2 shows test structures fabricated by a commercial PCB house, ExpressPCB Company. With these test structures, S-parameter data are obtained using a VNA and converted to Z-parameter data for initial value guess and optimization by the conversion equation set [10]:

$$\begin{aligned}
Z_{11} &= Z_0\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}\\
Z_{12} &= Z_0\frac{2S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}\\
Z_{21} &= Z_0\frac{2S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}\\
Z_{22} &= Z_0\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}.
\end{aligned} \qquad (4.6)$$

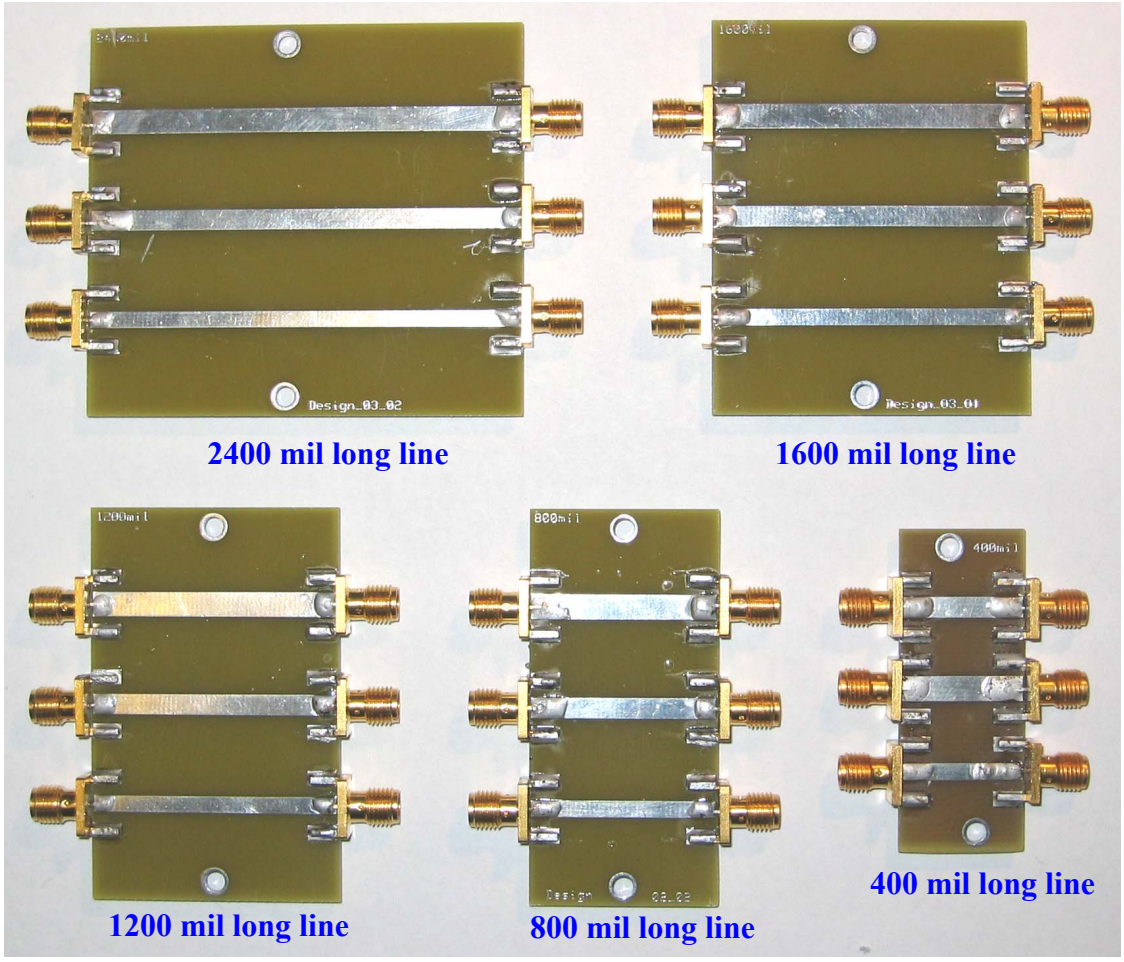



Figure 4.2. Test structure of the straight microstrip lines.

After conversion from measured S-parameter data, Figure 4.3 shows the Z-parameter data of three different long lines: the 400 mils, 800 mils and 2400 mils. From these results, we can see that the line has more resonance and its first resonance occurs at lower frequency as it increases in length.

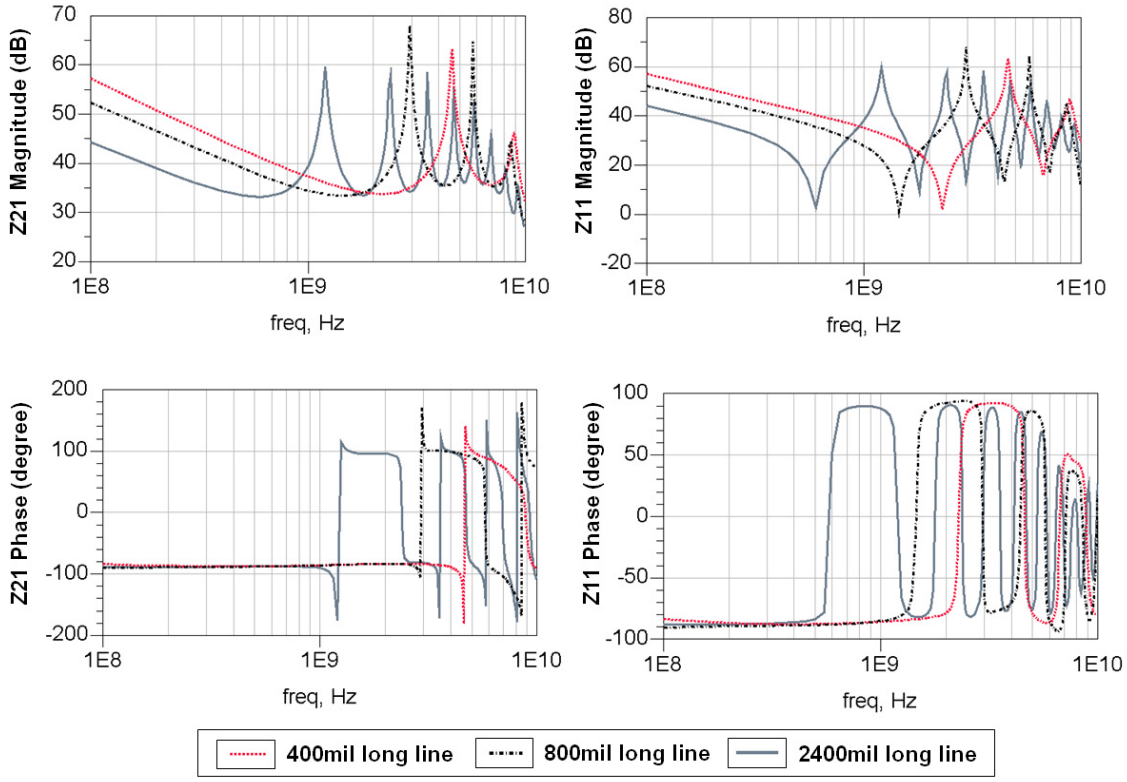
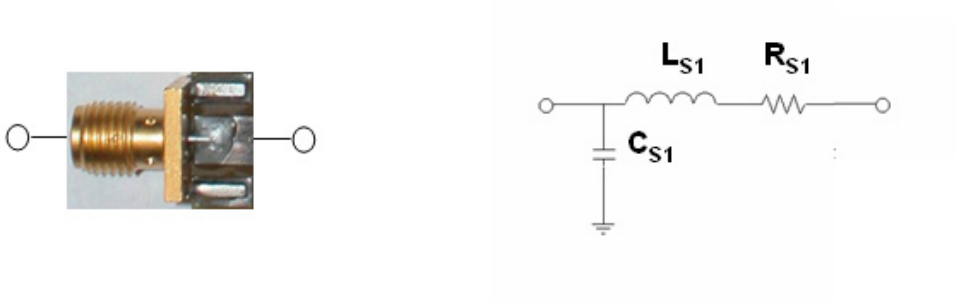



Figure 4.3. Measured Z-parameter data of the straight microstrip lines.

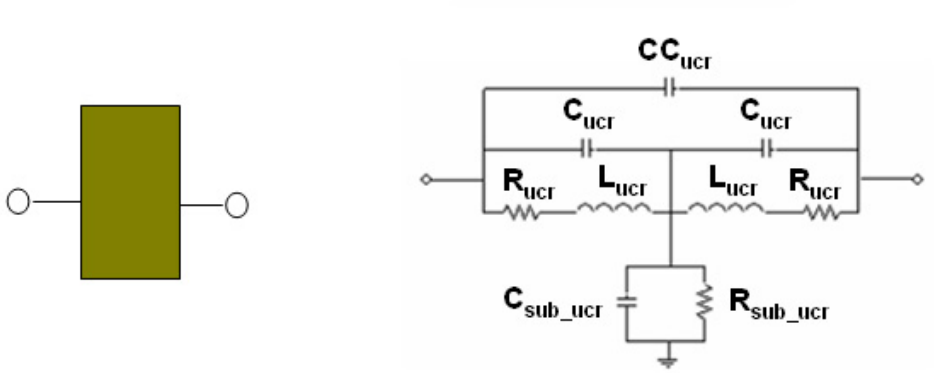
### 4.2.3. Equivalent circuit parameter extraction

Each building block is assigned its own equivalent circuit to model its electrical response. Generally, equivalent circuits consist of resistances, inductances and capacitances, and their combinations and equivalent circuit parameters (EC-parameters) are adjusted to follow the measurements. In this research work, a PEEC model structure is applied for the basic shape of the equivalent circuit that is the equivalent circuit of the rectangular building block as shown in Figure 4.4 (b). The equivalent circuit of the SMA connector building block, which is based on L-model, is shown in Figure 4.4 (a). Initial

values of the EC-parameters are estimated from a SMA connector structure and a 100-mil long line structure using impedance calculations at several measured data points.




(a) SMA connector building block




(b) Rectangular building block

Figure 4.4. Equivalent circuits of the straight microstrip lines.

With initial values obtained from the impedance calculation, the EC-parameters of the 400-mil long straight microstrip line are optimized by the ADS optimization tool as shown in Figure 4.5. The schematic involves four parts: S-parameter simulation set up, equivalent circuit block, optimization set-up and optimized EC-parameters. The S-parameter simulation setup is for the simulation of the measured S-parameter data blocks and equivalent circuits to optimize the EC-parameters. The optimization setup defines the

optimization methods and optimization goals. The expression of optimization goal, in this work, is relative difference between the measured Z-parameter data and the simulated Z-parameter data. In optimized EC-parameters, we enter initial values and optimization ranges of EC-parameters. As to the equivalent circuit block, the equivalent circuit of each rectangular building block, which is symbolized as we can see in Figure 4.5, is combined according to the building block diagram and then connected with equivalent circuits of the SMA connector.

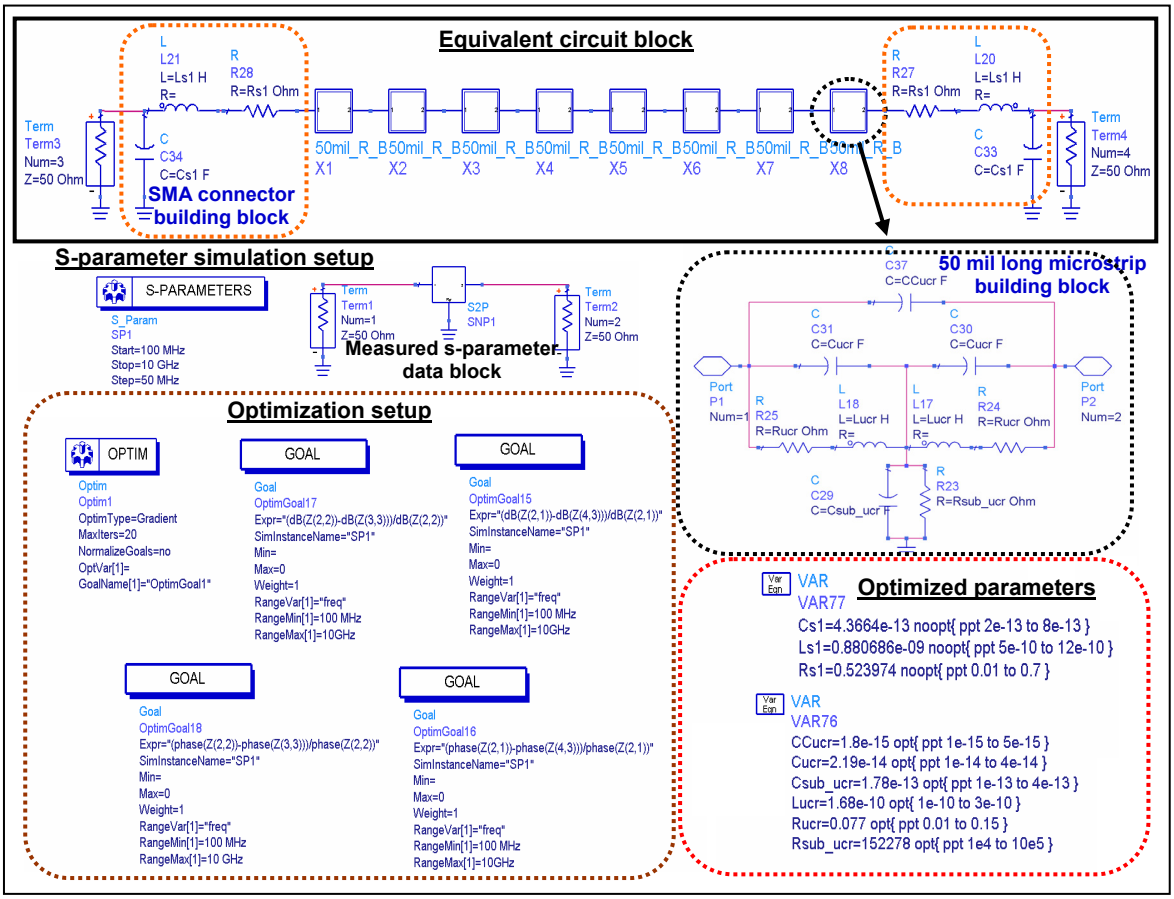



Figure 4.5. Schematic of optimization for the 400-mil long straight microstrip line.

Regarding the optimization process, the optimizer starts working with initial values and then evaluates the difference between the results generated from the equivalent circuits and measured data. After the first iteration, the search method determines the next EC-parameters for evaluating the difference. The optimizer finishes when it finds an optimized result in error tolerance range. Often, however, the optimizer finds the results as close to measured results as possible then times out at a preset iteration limit.

## 4.3. Momentum Simulation

The Method of momentum (MoM) has extensively been applied to the simulation of electromagnetic fields and interconnects since Harrington developed it in the beginning of the 1960's [35-37]. This method is theoretically based on the integral equation derived from Maxwell's equations.

Among simulation tools performing the numerical discretization and computation based on the MoM, the ADS momentum simulation tool is a simulation tool by which electrical engineers popularly simulate the electromagnetic response of unknown structures in their design. The momentum simulation employs a mixed potential integral equation (MPIE) for the mathematical formulation prior to the discretization, as given by Equation 4.7 [36]:

$$E(r) = \iint dSG(r, r') \bullet J(r), \tag{4.7}$$

where *E(r)* and *J(r)* are a known excitation of the problem and an unknown surface current, respectively and $G(r, r')$ and *dS* are the green dyadic of the layer and the surface differential, respectively. Since the surface currents on the conductor are the unknowns to be solved by the numerical method, the surface currents are discretized by the mesh patterning and the rooftop expansion [35, 36]. Here, a mesh represents a primitive grid-like cell of triangles and rectangles for discretization.

Along with the discretization, the Galerkin testing procedure [36, 52] converts the continuous integral equation into a matrix equation with finite basis functions, as given by Equation 4.8:

$$[V] = [Z] \bullet [I], \tag{4.8}$$

Where is [*V*] and [*I*] are a vector of the discretized effects in each mesh excited from ports and a vector of the discretized surfaces current in each mesh, and [*Z*] is called the interaction matrix representing electromagnetic interaction between the basis functions. By evaluation with the Green's dyadic and the interaction matrix elements, the interaction matrix turns into an equivalent network containing inductances and capacitances, which represents the physical reality. Using this equivalent network, therefore, the momentum simulation computes the unknown current values and then generates the S-parameter data.

In this thesis work, to evaluate the predictive modeling method, we achieve the momentum simulations corresponding to the predicted structures. The efficiency and accuracy of the momentum simulation, which are a tradeoff-relationship, directly depends on the frequency point and mesh density. For a reasonable momentum

simulation, we enter 20 mesh cells per wavelength and 100 frequency points in all momentum simulations. Figure 4.6 shows the layout of the 2400-mil long straight microstrip line for the momentum simulation. In this figure, we can see the grids of mesh cells which meet the given mesh density.

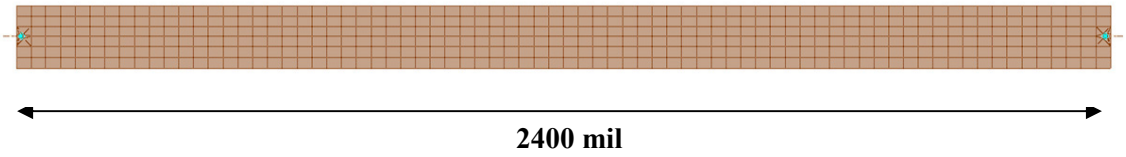



Figure 4.6. Layout of the 2400-mil long straight microstrip lines.

The momentum simulations using this layout are applied to obtain the frequency response. As the results of the momentum simulation, Figure 4.7 shows the Z-parameter data of the 2400-mil long straight microstrip line. In this figure, the Z-parameter data of the momentum simulation does not match those of the measurement well even at low frequencies. This discrepancy is due to omission of SMA connector effects. Hence, prior to the momentum simulation, effect of the SMA connectors should be taken into account on the momentum simulations. The use of the SMA connector equivalent circuit obtained in the predictive model is a good approach because this equivalent circuit was established based on several measured data sets. The simulation setup needed to add the effect of the SMA connectors is provided in Appendix B.1.

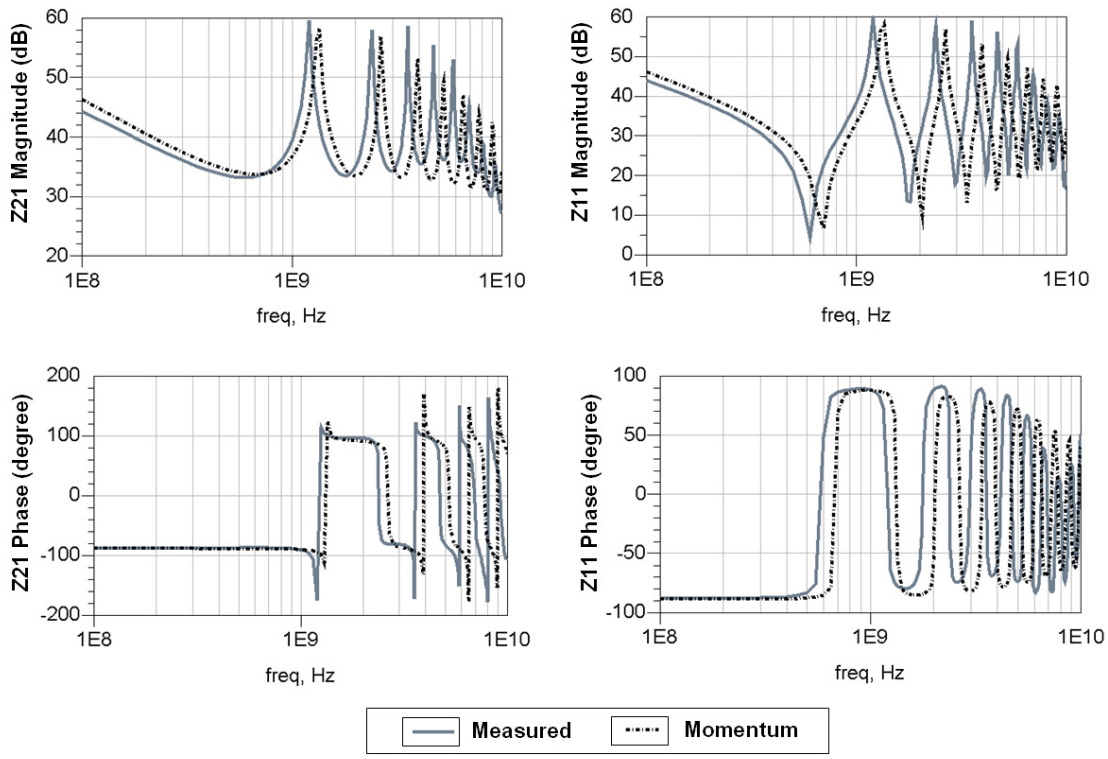



Figure 4.7. Momentum simulation results of the 2400-mil long straight microstrip line without SMA connector.

As shown in Figure 4.8, the Z-parameter data of the momentum simulation with the effect of the SMA connectors have a good agreement with those of measured data. From these results, it is inferred that the equivalent circuit of the SMA connector fairly interprets its real-world operation considering the standing of the ADS momentum simulation tool on performance for somewhat simple structures. This equivalent circuit of the SMA connector will be used for the momentum simulation of the advanced modeling works in Chapter 5.

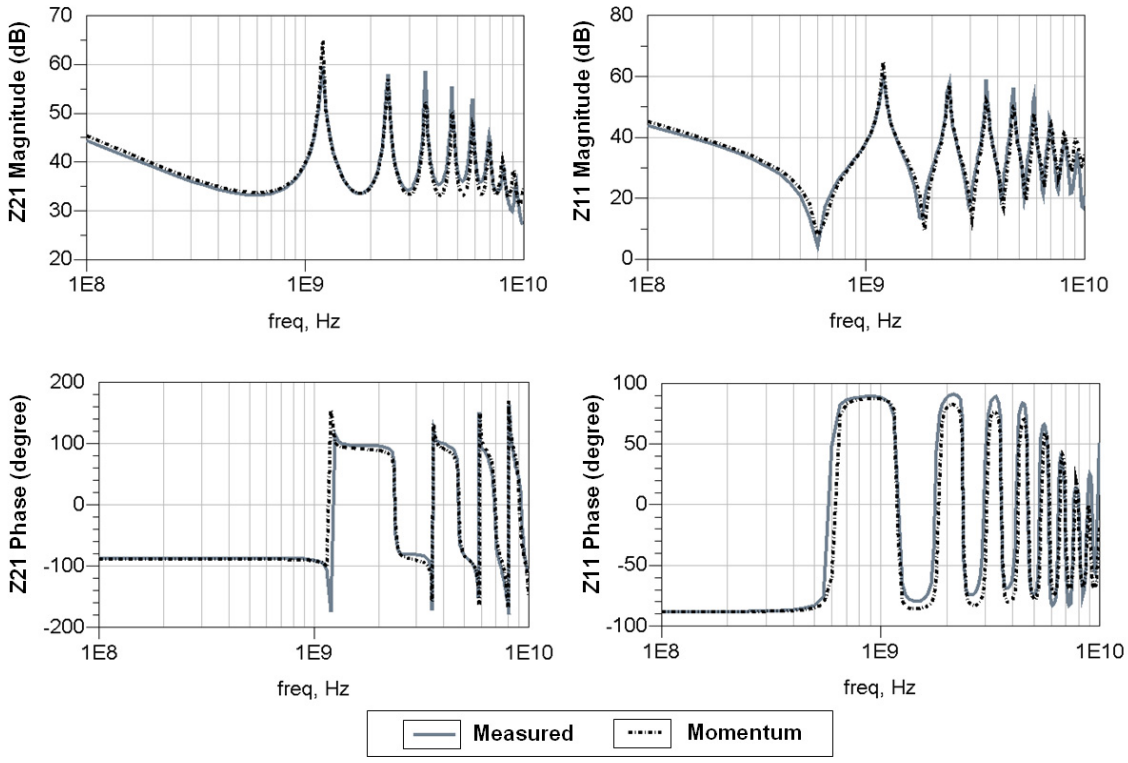



Figure 4.8. Momentum simulation results of the 2400-mil long straight microstrip line with SMA connector.

## 4.4. Results and Performance Comparison

By means of the optimization process, Z-parameter data of the predictive model, the 400-mil long straight microstrip line, is compared with the measured data as shown in Figure 4.9. The results indicate that the frequency response of the predictive model has a good agreement with that of the measurement in the range between 100 MHz and 10 GHz; particularly, in lower than 7 GHz, the results has a strong agreement.

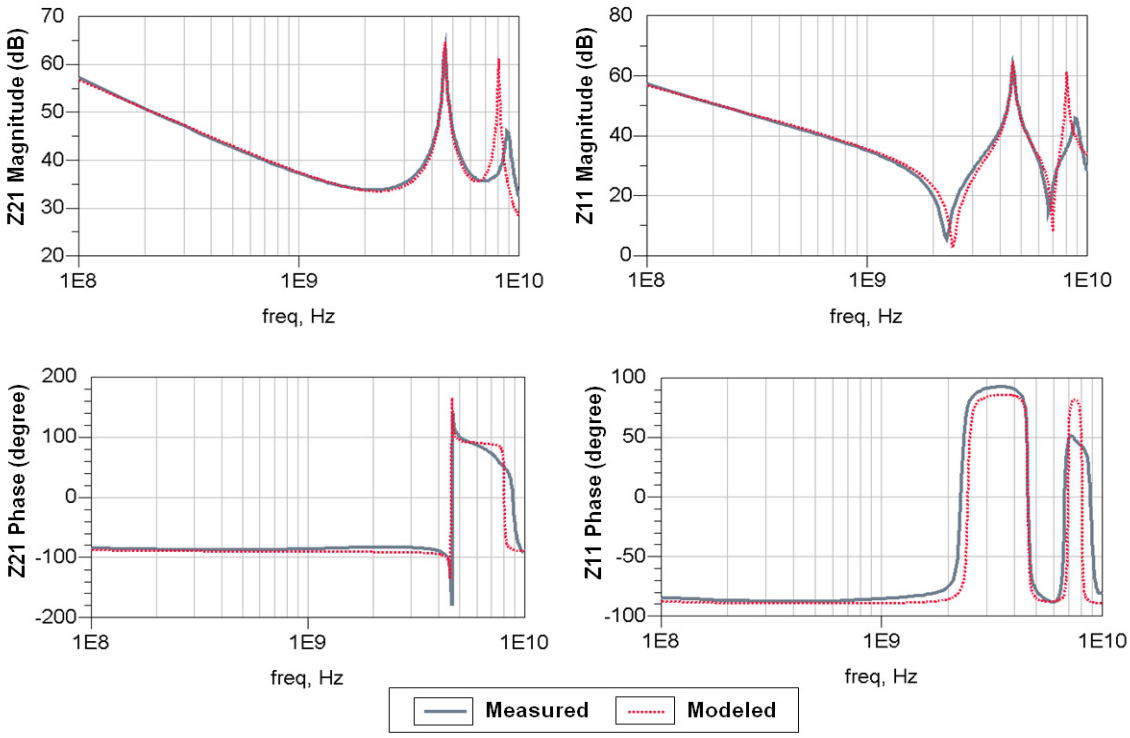



Figure 4.9. Optimized Z-parameter data of the 400-mil long straight microstrip line.

Based on this result, the model of the 400-mil long straight line should predict the longer lines by just adding more building blocks. The results of the predictions according to four different line lengths (800 mils, 1200 mils, 1600 mils and 2400 mils) are simultaneously compared with those of the measurement and those of the momentum simulation in terms of the Z-parameter data as shown in Figure 4.10, Figure 4.11, Figure 4.12 and Figure 4.13, respectively. These predicted results present reasonable agreements with the measurements, and this predictive modeling method has the comparable performance to the momentum simulation from the perspective of the frequency response.

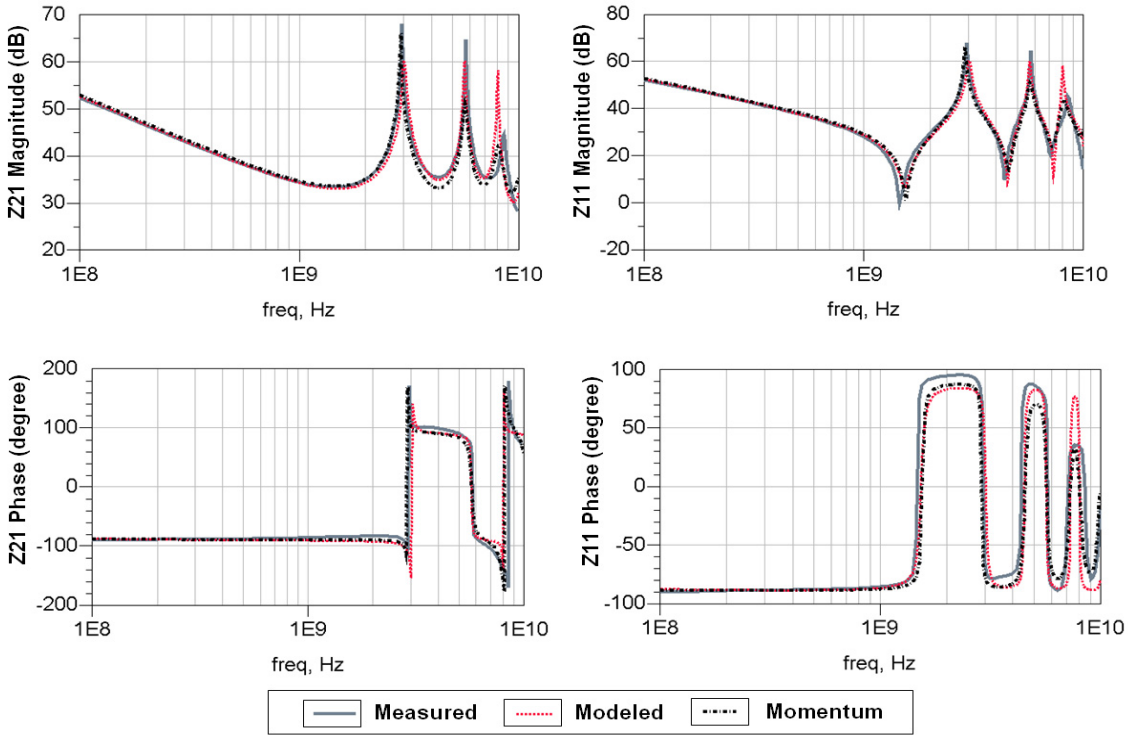



Figure 4.10. Predicted Z-parameter data of the 800-mil long straight microstrip line.

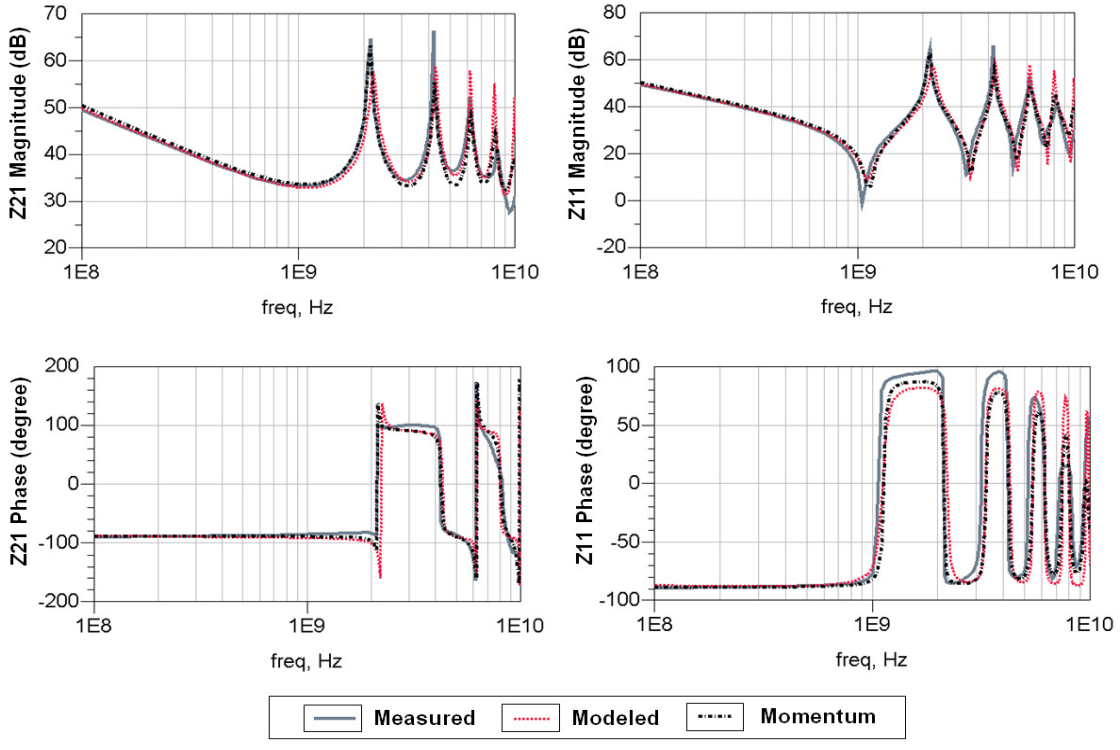



Figure 4.11. Predicted Z-parameter data of the 1200-mil long straight microstrip line.

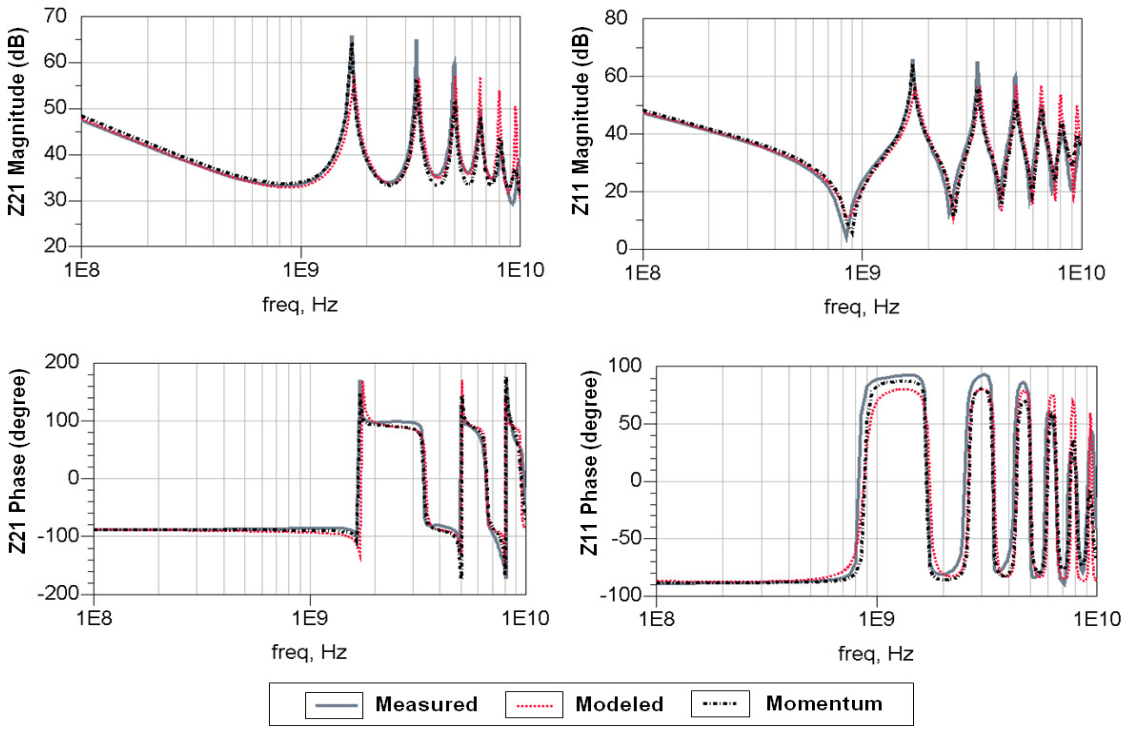



Figure 4.12. Predicted Z-parameter data of the 1600-mil long straight microstrip line.

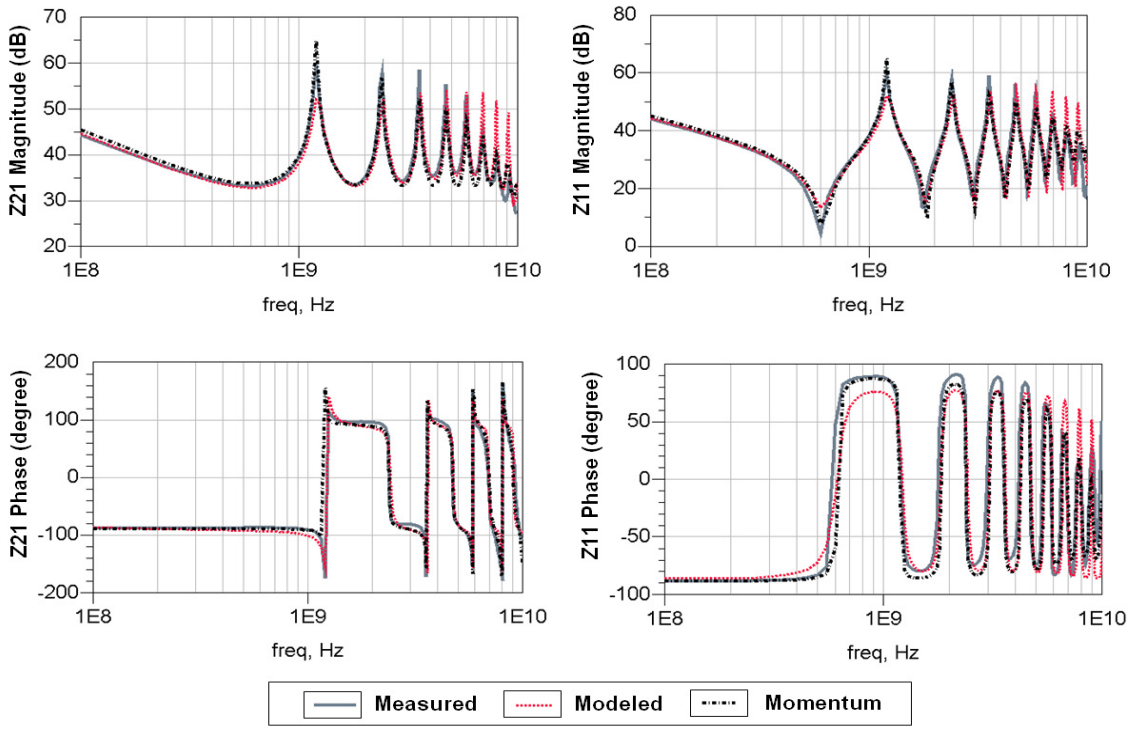
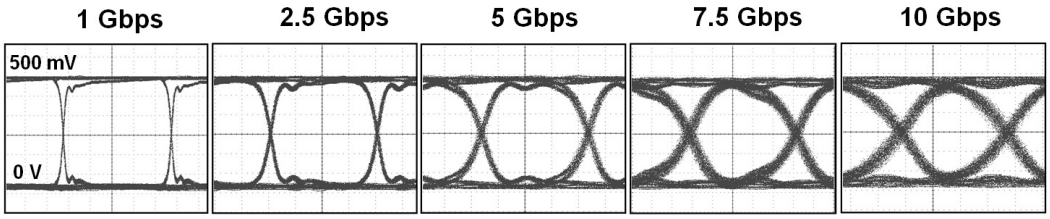


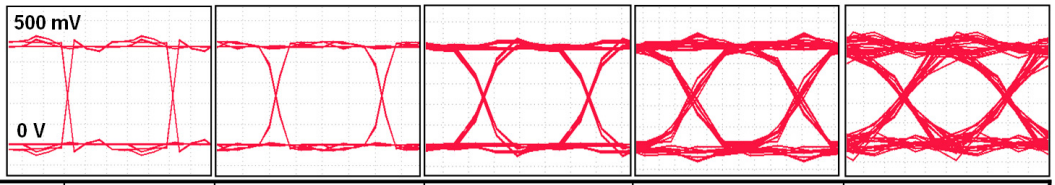

Figure 4.13. Predicted Z-parameter data of the 2400-mil long straight microstrip line.

Since circuit engineers verify the digital system in the time domain, the demonstration of the model in the time domain is another important evaluation for the accuracy. In this work, eye diagrams of the 2400-mil long straight microstrip line are used to verify the predicted time domain response. The measured eye diagrams and the eye diagrams simulated from the predictive model are obtained at five data rates (1 Gbps, 2.5 Gbps, 5 Gbps, 7.5 Gbps and 10 Gbps) as shown in Figure 4.14 (a) and Figure 4.14 (c).



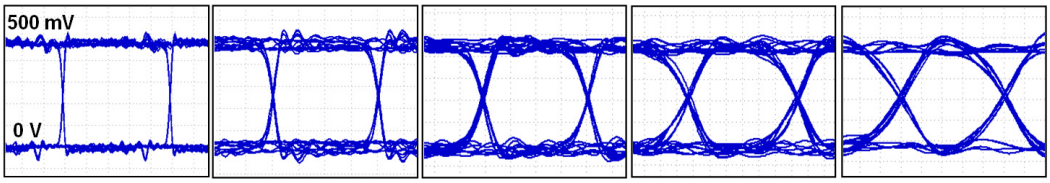

| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 93.75 % | 88.33 % | 83.33 % | 81.25 % | 72.92 % |
| Jitter [UI] | 1.18 % | 2.75 % | 6.67 % | 10.98 % | 14.44 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 89.58 % | 87.50 % | 86.25 % | 80.42 % | 70.83 % |
| Jitter [UI] | 0.81 % | 1.57 % | 4.02 % | 9.41 % | 10.36 % |

(b) Simulated eye diagrams from the S-parameter data




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 89.80 % | 85.71 % | 84.34 % | 81.63 % | 72.52 % |
| Jitter [UI] | 0.98 % | 2.75 % | 4.42 % | 5.88 % | 8.03 % |

(c) Simulated eye diagrams from the predictive model

Figure 4.14. Comparison of the eye diagrams of the 2400-mil long straight microstrip line.

Additionally, the eye diagrams simulated from the measured S-parameter data block are shown in Figure 4.14 (b). All eye diagrams are obtained from $2^7$-1 PRBs patterns. The eye diagram simulation setup of the measured S-parameter data block and that of the predictive model are provided in Appendix B.2 and Appendix B.3, respectively. According to the comparison of the eye diagrams, the accuracy of the predictive model in the time domain is good to represent the electrical reality and thus the predictive model equally works equally well in the time and frequency domains.

For the straight microstrip lines, since the predictive model has comparable accuracy to the momentum simulation, the evaluation of efficiency can be a good motivation for this work. With the resource of a UNIX computer of a 500 MHz Ultra SPARC IIi CPU with 2 G-byte memory, we measure the simulation times of the momentum simulation and those of the predictive model to evaluate their efficiency. Figure 4.15 shows the simulation times of the momentum simulation and the predictive model according to the different line length. In this figure, the predictive model fulfills its simulation in a few seconds regardless of the line lengths. As to the momentum simulation, however, its simulation time dramatically increases as the microstrip line length increases. Particularly, in the case of the 2400-mil long straight microstrip line, the momentum simulation takes over 9 hours whereas the prediction is completed in a few seconds. Therefore, from the viewpoint of efficiency, the application of the predictive modeling method for the straight microstrip lines has a considerable advantage in comparison to the momentum simulation, although they are equally applicable methods with good accuracy.

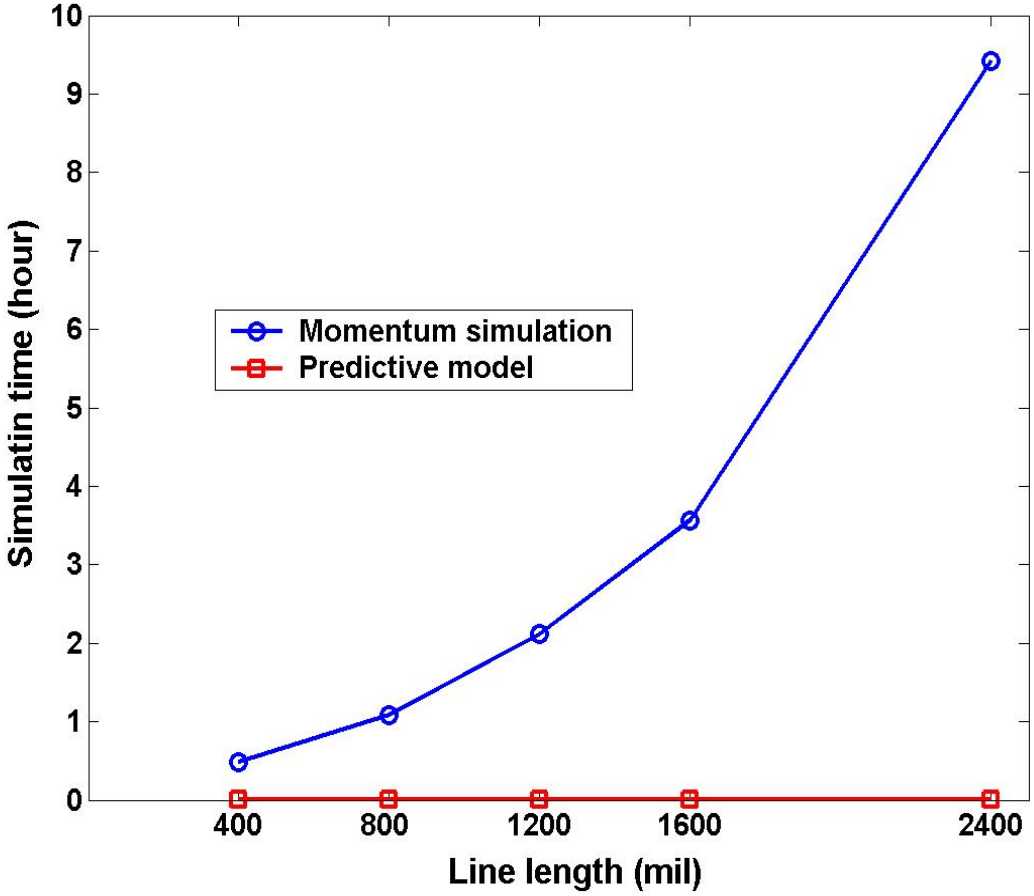



Figure 4.15. Comparison of the simulation times regarding line length of the straight microstrip lines.

## 4.5. Summary

In this chapter, the predictive measurement-based PEEC modeling method described in the last chapter has been applied for high-frequency straight microstrip interconnects on FR4 board. The results of this application have demonstrated the usefulness of the predictive modeling method in comparison of the momentum simulations and measurements.

In the modeling process, the building blocks of the straight microstrip lines have been determined by the calculation of a tenth wavelength, and the test structures have been designed and tested to obtain both frequency and time responses with variations of the line lengths. The equivalent circuits of the building blocks have been established based on a PEEC model and geometrical variation, and the EC-parameters have been optimized by the ADS optimizers. With the optimization results, the prediction has been achieved and compared with the measurements and the momentum simulations in terms of the accuracy and efficiency. Based on compared results, the predictive model has been evaluated for its usefulness and motivation.

The evaluations of the accuracy indicate that the responses of the predictive model reasonably conform to the measurements and are comparable to the momentum simulation. As to the evaluation of efficiency, the predictive model is a strong motivation owing to the rapid simulation in contrast with the slow momentum simulation. Therefore, in this chapter, we have achieved the first demonstration of applying the predictive measurement-based PEEC modeling method for high-frequency interconnects on low-cost FR4 board. An advanced modeling work will be discussed in the next chapter.

# CHAPTER V

# MODELING OF SERPENTINE STRUCTURES

## 5.1. Introduction

Today, the digital systems encounter a great demand for the miniaturization and thus interconnects in this system inevitably adopt many geometrical discontinuities which were explained in Section 2.4.2. Although the discontinuities provide a geometrical advantage, they result in poor signal integrity. For this reason, the effects of discontinuities should be considered in the modeling works. Among the discontinuities, bending structure and coupling effects are inevitable to route the system path. Hence, the serpentine structures are fitting for these modeling works because they contain bending structures and coupling effects and also because they are appropriate structures for the delay lines in digital systems.

In this chapter, as an advanced modeling work, the serpentine structures are applied for the predictive modeling method described here. The steps of modeling procedures are identical to those of the last chapter, and additionally interpolation techniques are used to enhance the flexibility of the predictive model. Eventually, the predictive model of the serpentine structure on FR4 boards is evaluated in comparison with the measurements and the momentum simulations.

## 5.2. Modeling Description

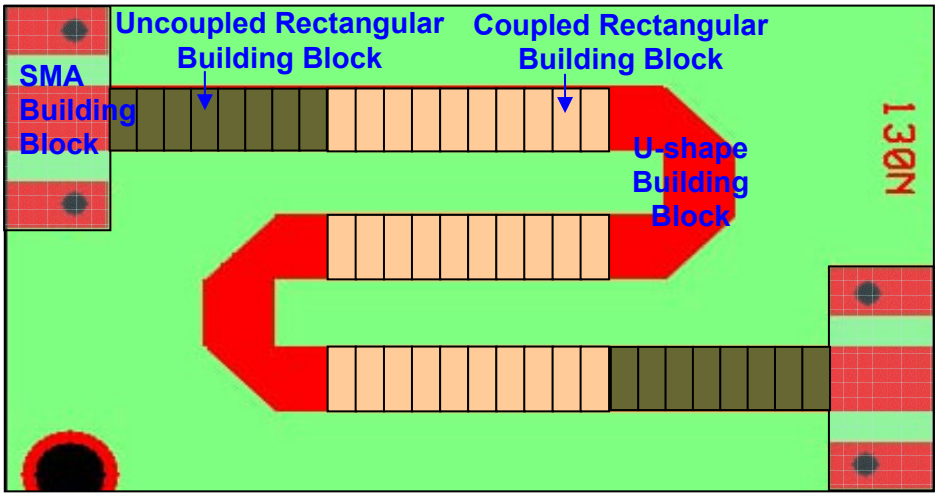
### 5.2.1. Determination of building blocks

The serpentine structures described in this chapter are defined according to the number of 180-degree turns, which is identical to the number of U shapes. For example, if the serpentine structure has 3 turns, this structure are called 3-turn serpentine structure. In particular, based on their shapes, 2-turn and 3-turn serpentine structures herein are called N-shaped and M-shaped structures, respectively.

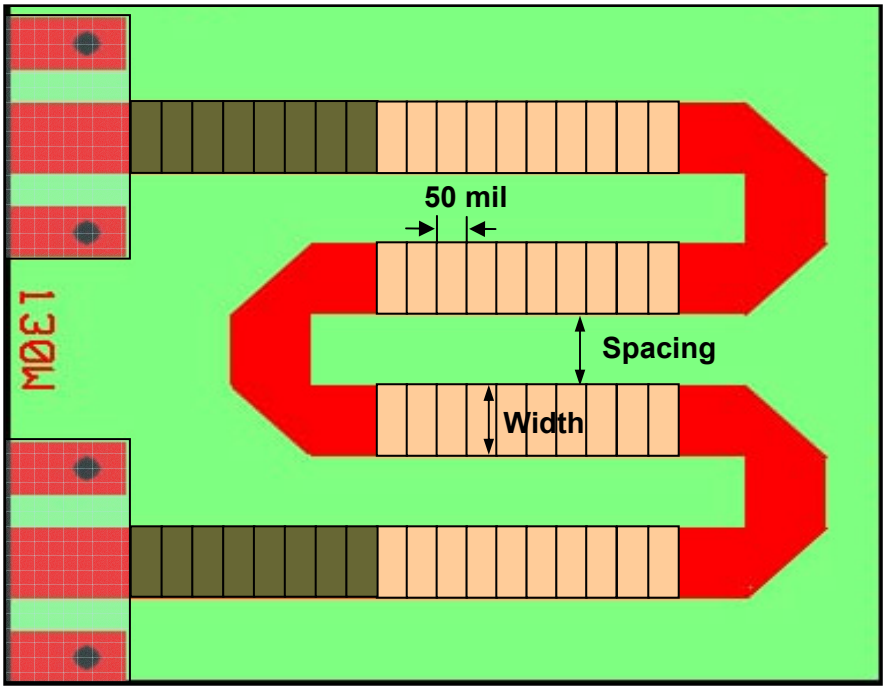
The serpentine structure consists of four different kinds of building blocks: the SMA connector building block, uncoupled rectangular building block, coupled rectangular building block and U-shaped building block. The SMA connector building block and uncoupled building block are the same as those of the straight microstrip line in the last chapter. As calculated in Section 4.2.1, the straight lines of the serpentine structures are divided into 50-mil long uncoupled rectangular building blocks and 50-mil long coupled rectangular building blocks in the sense of coupling effects. The other structures, U-shaped structure and SMA connector, are represented by a respective lumped building block.

More specifically, the N-shaped structure to be optimized has two SMA connector building blocks, sixteen uncoupled rectangular building blocks, thirty coupled rectangular building blocks and two U-shaped building blocks as shown in Figure 5.1 (a). On the other hand, the M-shaped structure predicted from the N-shaped structure adds a U-shaped building block and ten coupled building blocks to the total building blocks of the

N-shaped structure as shown in Figure 5.1 (b). In the same manner, the building block of the structure having more than 3 turns can be determined.




(a) N-shape serpentine test structure




(b) M-shape serpentine test structure

Figure 5.1. Building block diagrams of the serpentine structures.

### 5.2.2. Design and measurements

The serpentine structures with 130-mil width are designed and fabricated as the topology of 50-Ω characteristic impedance at 10 GHz, as mentioned in Section 4.2.2. Additionally, at the center of the 130-mil wide serpentine structure with 130-mil spacing, the serpentine structures with three different line widths and three different spacing are designed and fabricated for the predictions by interpolation. More specifically, 104 mils, 130 mils and 156 mils are used for the line widths. In addition, 0.5S, 1S and 2S are used for the spacings where 0.5S, 1S and 2S denote half, once and twice the line width. For instance, if the line width is 130 mils, then 0.5S, 1S and 2S represent 60-mil, 130-mil and 260-mil spacing, respectively. Figure 5.2 shows test structures to be used for the modeling of the serpentine structures. In the figure, mitred 90-degree corners are used to reduce the discontinuity effect.

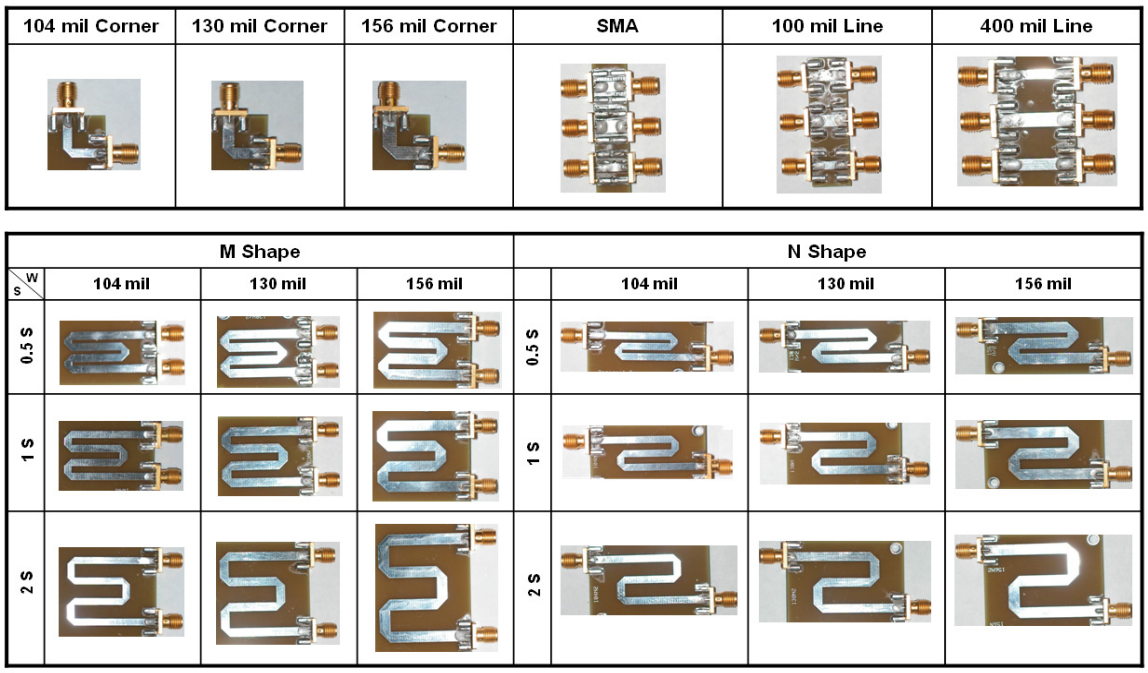
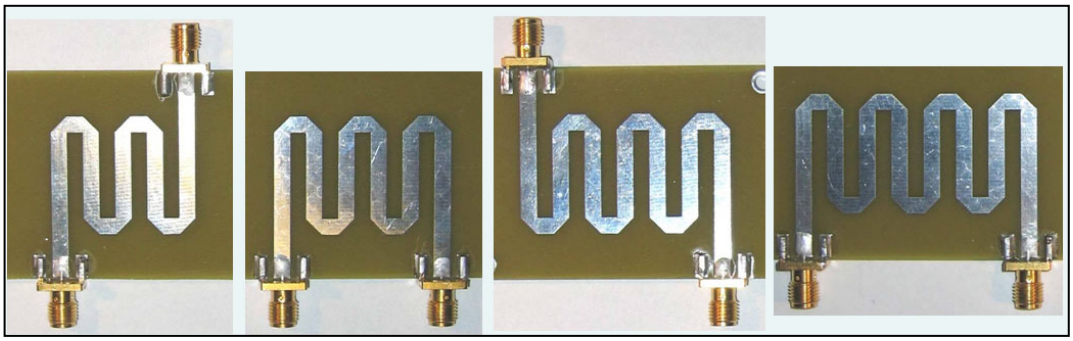



Figure 5.2. Test structures showing matrix of line widths and line-to-line spacings used.

For the predictions of more extended serpentine structures, four additional serpentine structures, which are 4-turn, 5-turn, 6-turn and 7-turn serpentine structures as shown in Figure 5.3, are designed and fabricated to validate their scalability



(a) (b) (c) (d)

Figure 5.3. Serpentine structures with: (a) 4 turns, (b) 5 turns, (c) 6 turns, and (d) 7 turns.

Using these test structures, their frequency and time response are obtained for optimization and verification. As for the frequency response, Figure 5.4 shows the comparison of the measured Z-parameter data of the N-shaped, M-shaped and 7-turn serpentine structures. As we can see in this figure, as the number of turns increases, the Z-parameter data have more resonances and predictive variation. From this intuitive information, we may expect that the predictive model obtained using the N-shaped structure may predict the electrical responses of the M-shaped structure or more extend structures such as the 7-turn serpentine structure. As to the time responses, we will show them with the modeling eye diagrams in Section 5.4.

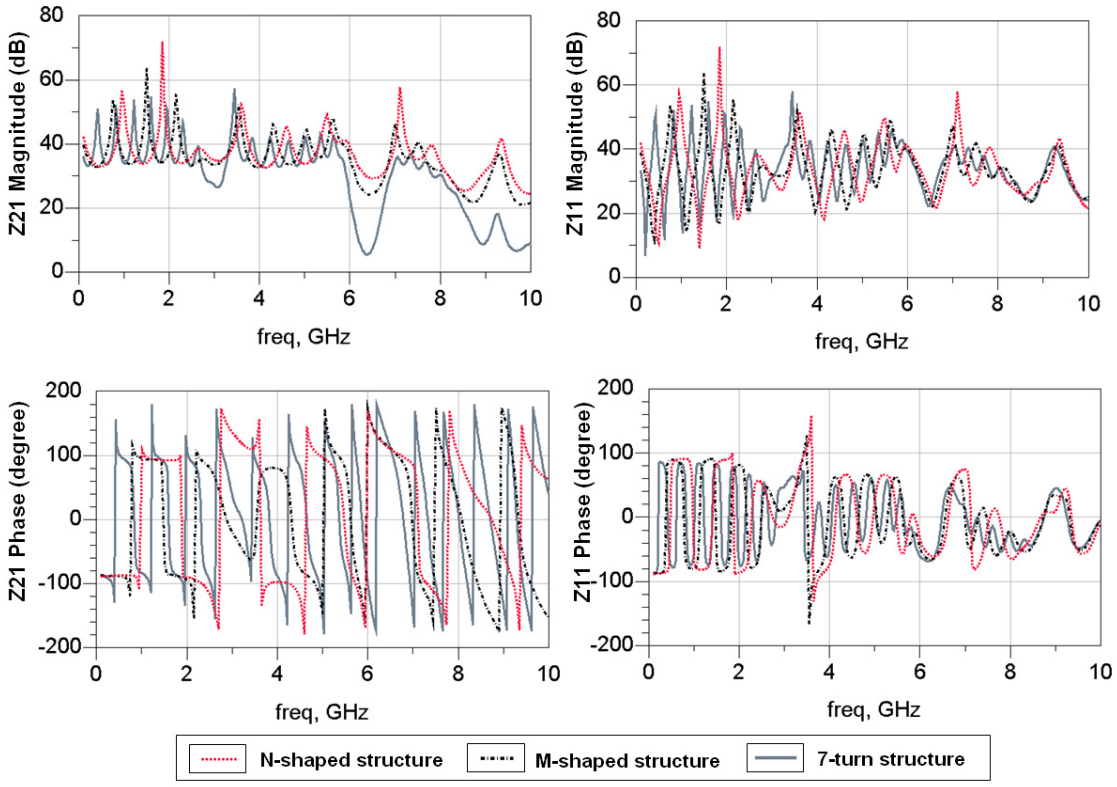



Figure 5.4. Measured Z-parameter data of the serpentine structures.

### 5.2.3. Equivalent circuit parameter extraction

Equivalent circuits of building blocks representing the serpentine structures are derived from the PEEC model and modified with respect to their geometry. As to the equivalent circuits of the SMA connector building block and uncoupled rectangular building block, the serpentine structure contains the same equivalent circuits of the straight microstrip lines described in Section 4.2.3 as shown in Figure 5.5 (a) and (b).

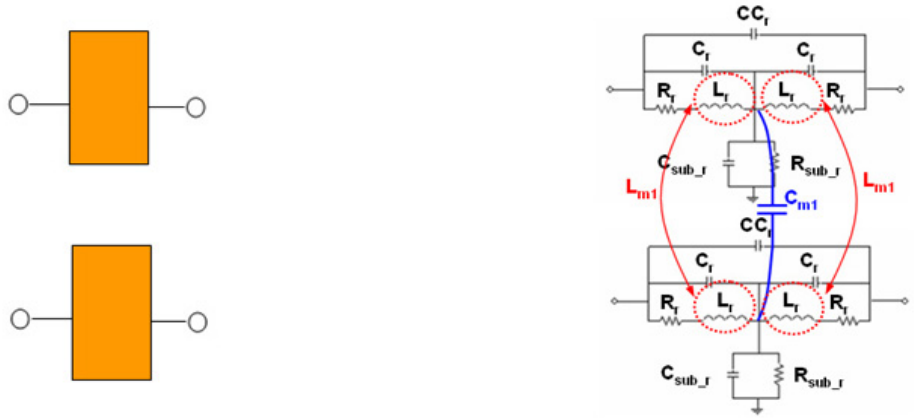
In addition to the equivalent circuits of the SMA connector building block and the uncoupled rectangular building block, the serpentine structure has the equivalent circuits of the coupled rectangular building block and U-shaped building block. The equivalent

circuit of the coupled rectangular building block is a simple combination of two separated uncoupled rectangular building blocks with a mutual inductance and a mutual capacitance between the adjacent neighbors as shown in Figure 5.5 (c). The U-shaped building block has two right-angle bending structures. The equivalent circuit of the U-shaped building block is the modified PEEC model with an internal mutual capacitance and an internal mutual inductance as shown in Figure 5.5 (d). All building blocks are combined to express the serpentine structures as shown in Figure 5.6.


(a) SMA connector building block


(b) Uncoupled rectangular building block

Figure 5.5. Equivalent circuits of the serpentine structure.




(c) Coupled rectangular building block


(d) U-shaped building block

Figure 5.5. Equivalent circuits of the serpentine structure (continued).

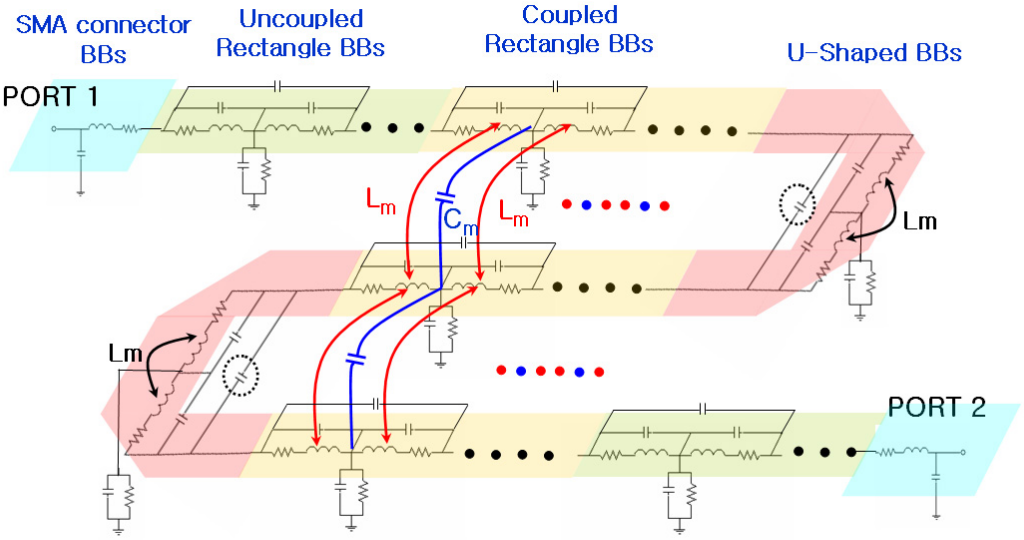



Figure 5.6. Combination of equivalent circuits for the N-shaped serpentine structure.

The equivalent circuit parameters (EC-parameters) of the N-shaped serpentine structure are optimized by the ADS optimizers. The optimization is achieved using the customized schematic as shown in Figure 5.7. The hierarchical block of equivalent circuits in this schematic facilitates the optimization process.

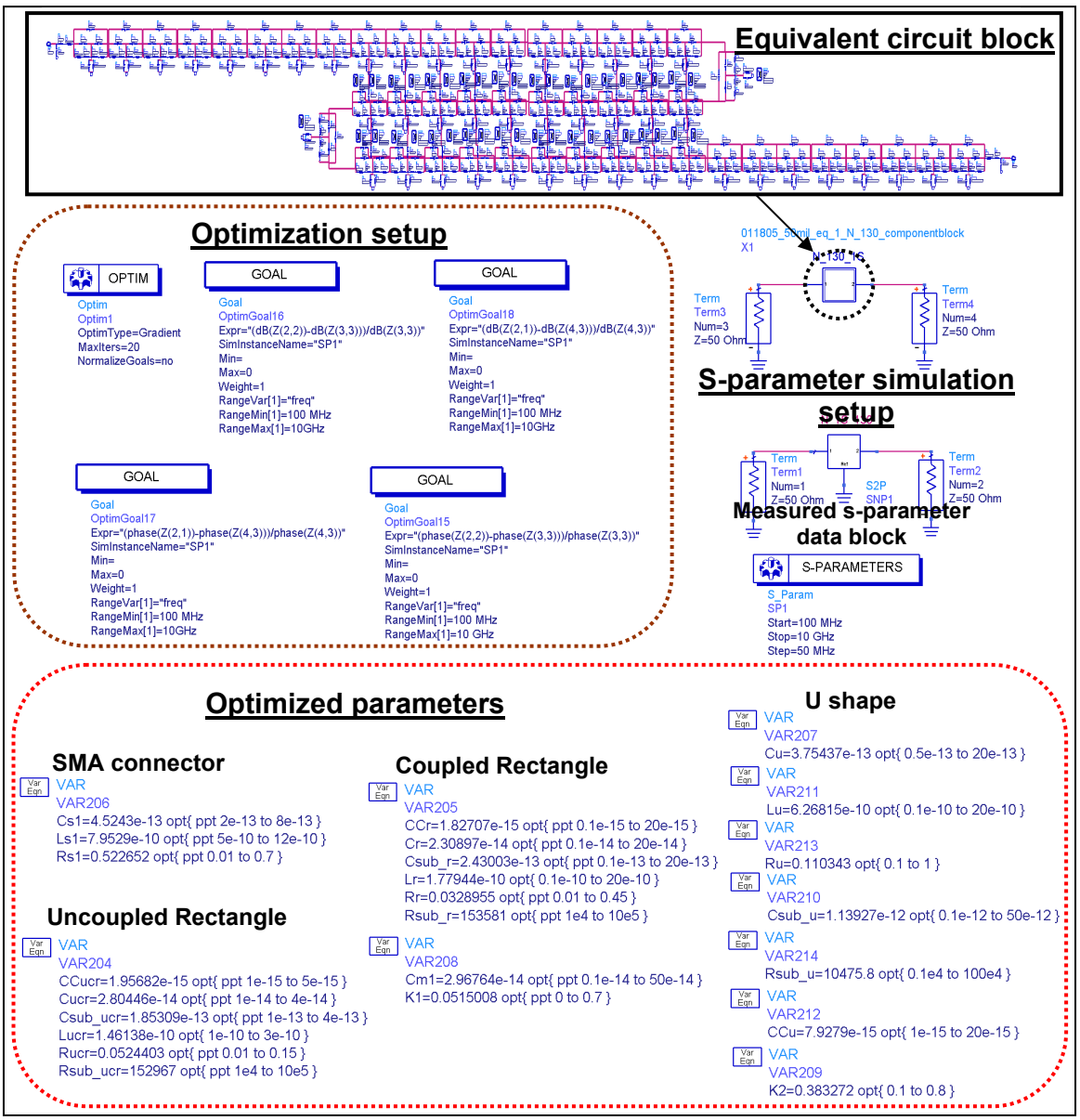



Figure 5.7. Schematic of the optimization for the N-shaped serpentine structure.

## 5.3. Momentum Simulation

The layout of the serpentine structure is drawn as shown in Figure 5.8 to achieve the momentum simulation. For the momentum simulation, we set up 20 cells per wavelength for the mesh density and 100 points for the frequency step between 100 MHz and 10 GHz. The SMA connector effects are taken into account in this momentum simulation by adding the equivalent circuit of the SMA connector used for the straight microstrip lines whose accuracy was discussed in Section 4.3. The momentum simulations under the same setup are applied for all the serpentine structures.

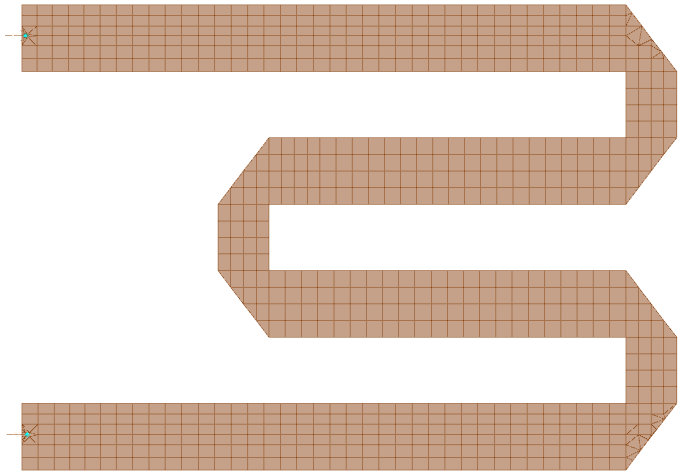


Figure 5.8. Layout of the M-shaped serpentine structure.

Figure 5.9 shows Z-parameter data of the M-shaped structure obtained by the momentum simulation; moreover, these results are compared with the measured data. From this comparison, while the momentum simulation has a good agreement with the measurements in less than 5 GHz, its prediction is ruined over 5 GHz.

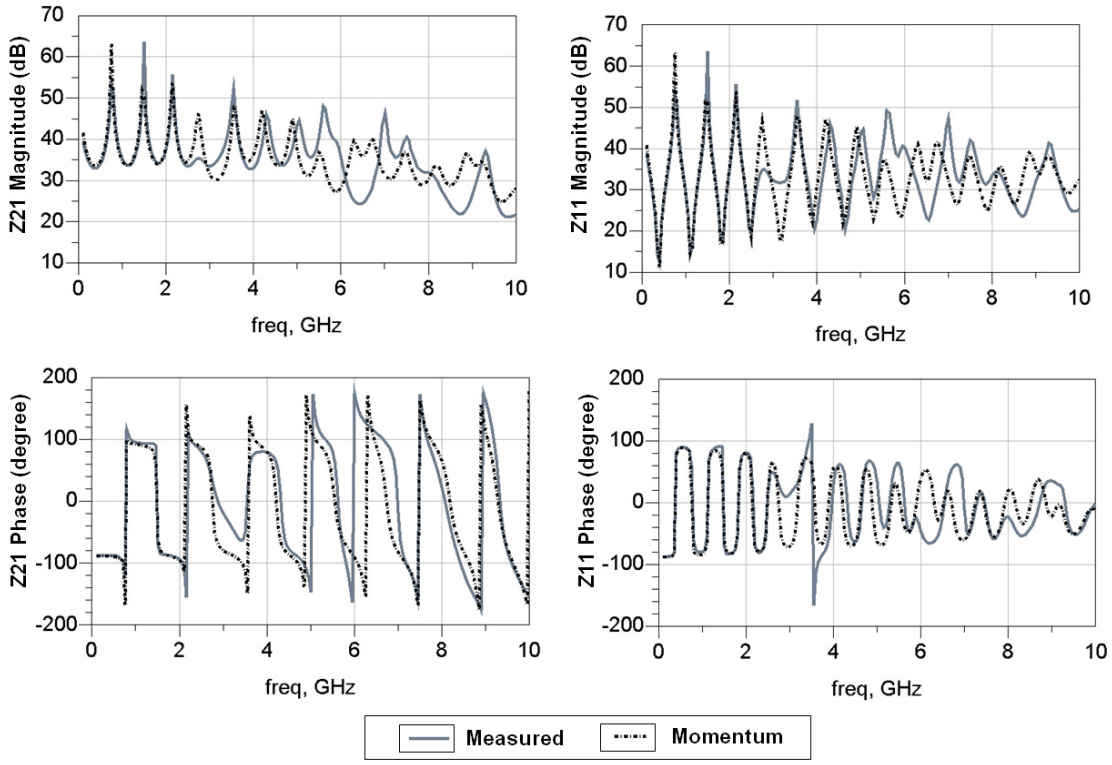



Figure 5.9. Momentum simulation results of the M-shaped serpentine structure.

## 5.4. Results and Performance Comparison

With the optimized EC-parameters, the Z-parameter data of the N-shaped structure, which is the predictive model, are compared with measured data. As we can see in Figure 5.10, the results show a good agreement in broad bandwidth. With this verification of the predictive model, we observe that the optimized N-shaped structure predicts the M-shaped structure. Figure 5.11 shows that comparison of the Z-parameter data to evaluate accuracy in the frequency domain. The results indicate that the M-shaped structure is predictable from the N-shaped structure and has more conformable frequency response to measurements than the momentum simulation does.

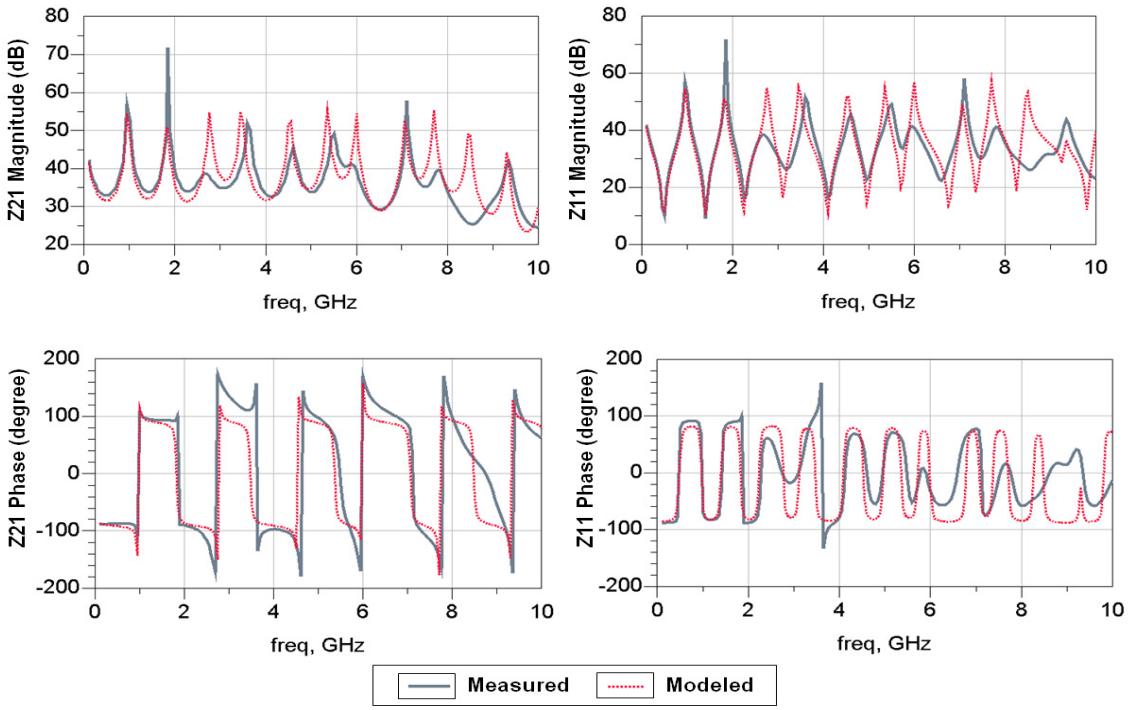



Figure 5.10. Optimized Z-parameter data of the N-shaped serpentine structure.

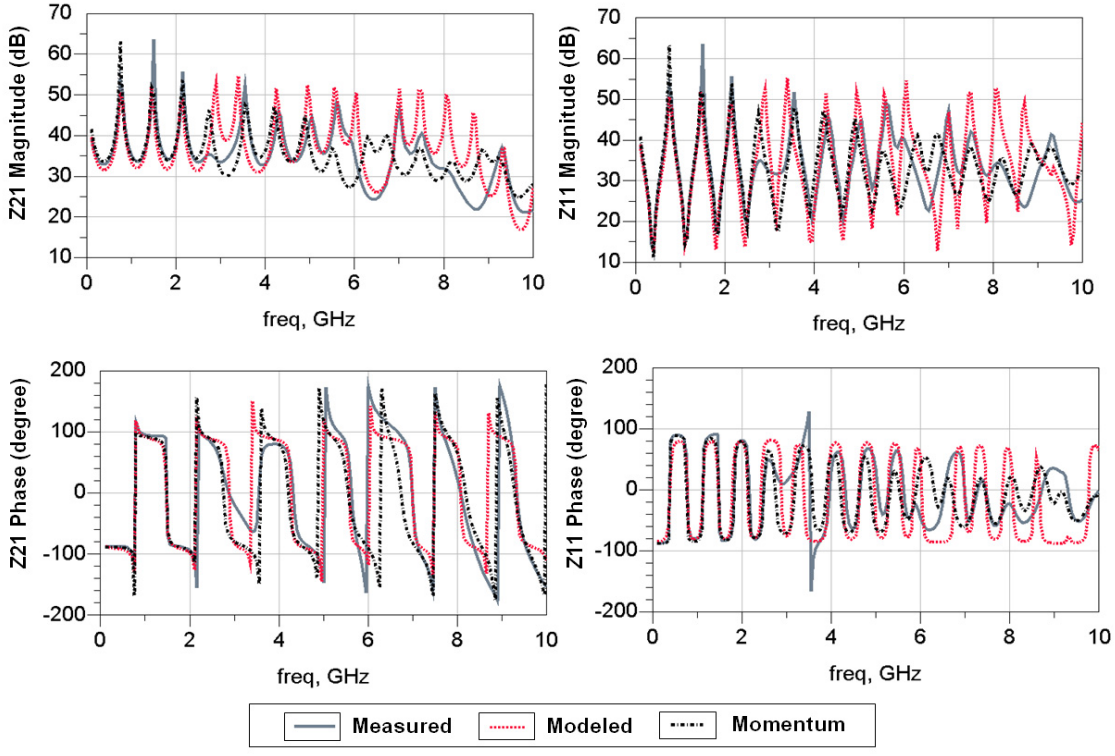
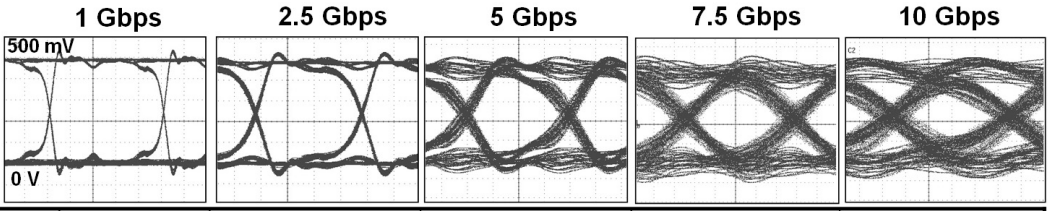


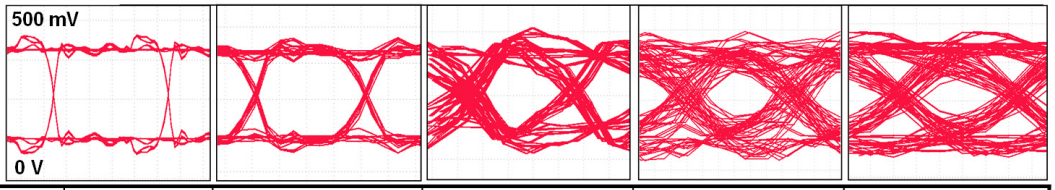

Figure 5.11. Predicted Z-parameter data of the M-shaped serpentine structure.

In the same manner as the case of the straight microstrip line in the last chapter, transient simulations in the ADS execute the time domain analysis, resulting in eye diagrams from 1 Gbps to 10 Gbps. Figure 5.12 (a) shows the eye diagrams of the M-shaped structure measured by the time-response measurement setup, and Figure 5.12 (c) shows its eye diagrams simulated with the equivalent circuits of the predictive model. Figure 5.12 (b) is its eye diagrams simulated from the measured frequency data by the Fast Fourier Transform (FFT) and convolution analysis.



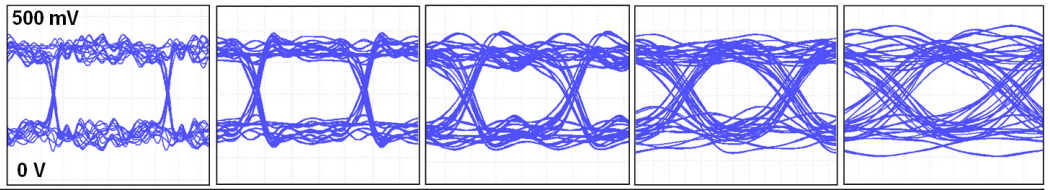

| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 81.13 % | 71.70 % | 60.77 % | 48.08 % | 35.38 % |
| Jitter [UI] | 1.27 % | 4.37 % | 16.33 % | 24.62 % | 32.14 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 79.17 % | 70.80 % | 57.69 % | 40.38 % | 32.69 % |
| Jitter [UI] | 1.03 % | 5.02 % | 22.18 % | 31.48 % | 33.33 % |

(b) Simulated eye diagrams from the S-parameter data




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 76.09 % | 67.39 % | 58.67 % | 49.62 % | 39.23 % |
| Jitter [UI] | 1.91 % | 6.25 % | 15.32 % | 22.75 % | 35.71 % |

(c) Simulated eye diagrams from the predictive model

Figure 5.12. Comparison of eye diagrams of the M-shaped serpentine structure.

The comparison of the eye diagrams indicates that the predicted time domain response of M-shaped serpentine structure from the predictive model have a good agreement with the measured time domain response.

In this section, we have demonstrated the prediction of the M-shaped serpentine structure from the predictive model. Now, in the same manner, the structures containing more than 3 turns are predicted by the predictive model for the extensive demonstration. Figure 5.13, Figure 5.14, Figure 5.15 and Figure 5.16 show the predicted Z-parameter data of 4- , 5- , 6- and 7- turn serpentine structures, respectively. From these Z-parameter data, we observe that as the number of turns increases, the difference between the predictions and measurements increases. In spite of this increasing difference, the predictions still have a fair agreement with the measurements: especially in the results of the predictive model of the 7-turn serpentine structure as compared with those of its momentum simulation. The comparison indicates that the prediction has a fair agreement with the measurements whereas the momentum simulation cannot conform to the measurement at higher than 5 GHz frequency as shown in Figure 5.16.

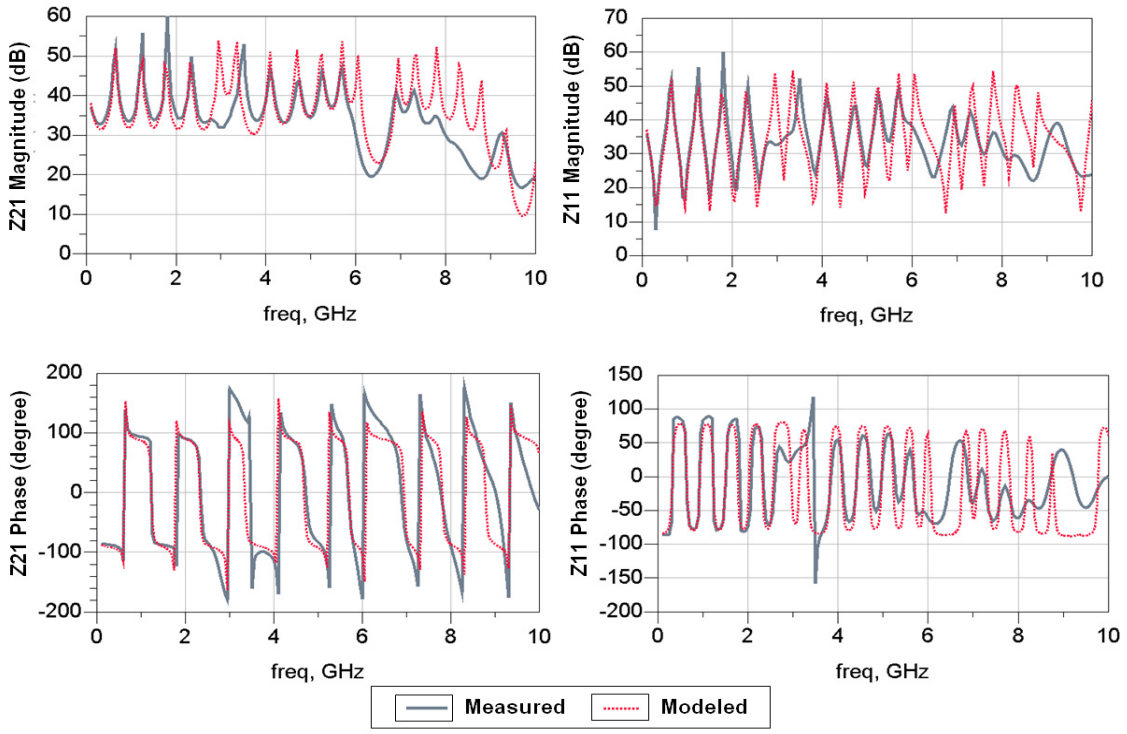



Figure 5.13. Predicted Z-parameter data of the 4-turn serpentine structure.

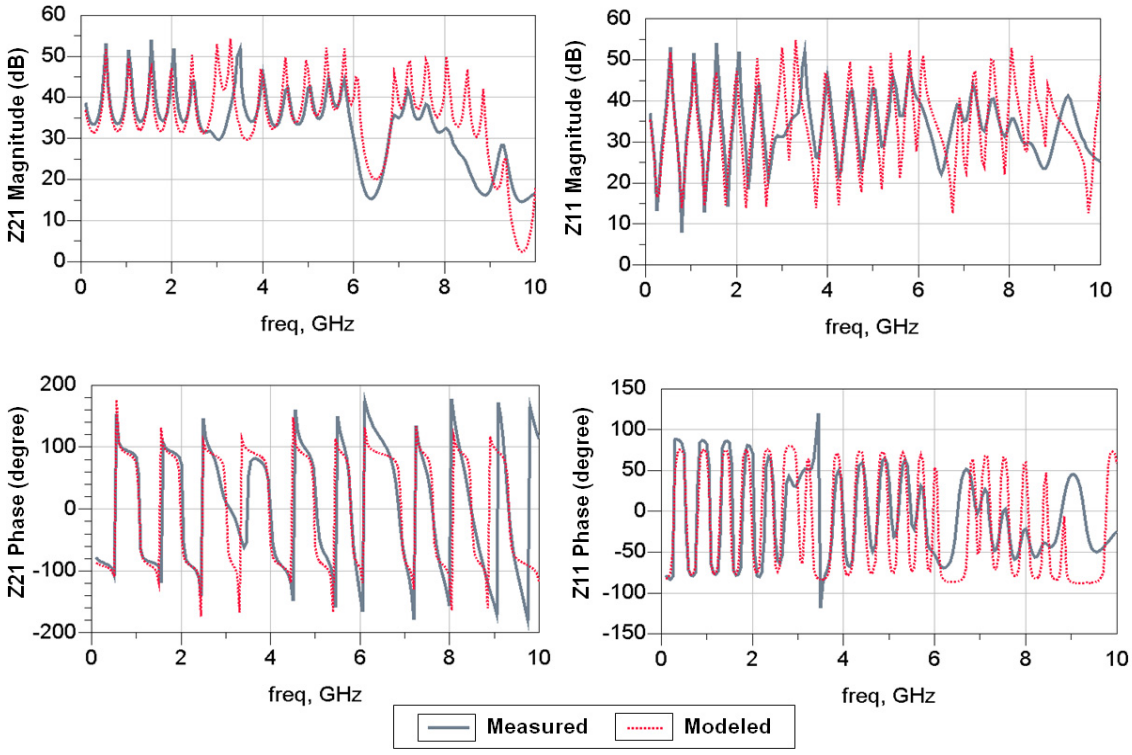



Figure 5.14. Predicted Z-parameter data of the 5-turn serpentine structure.

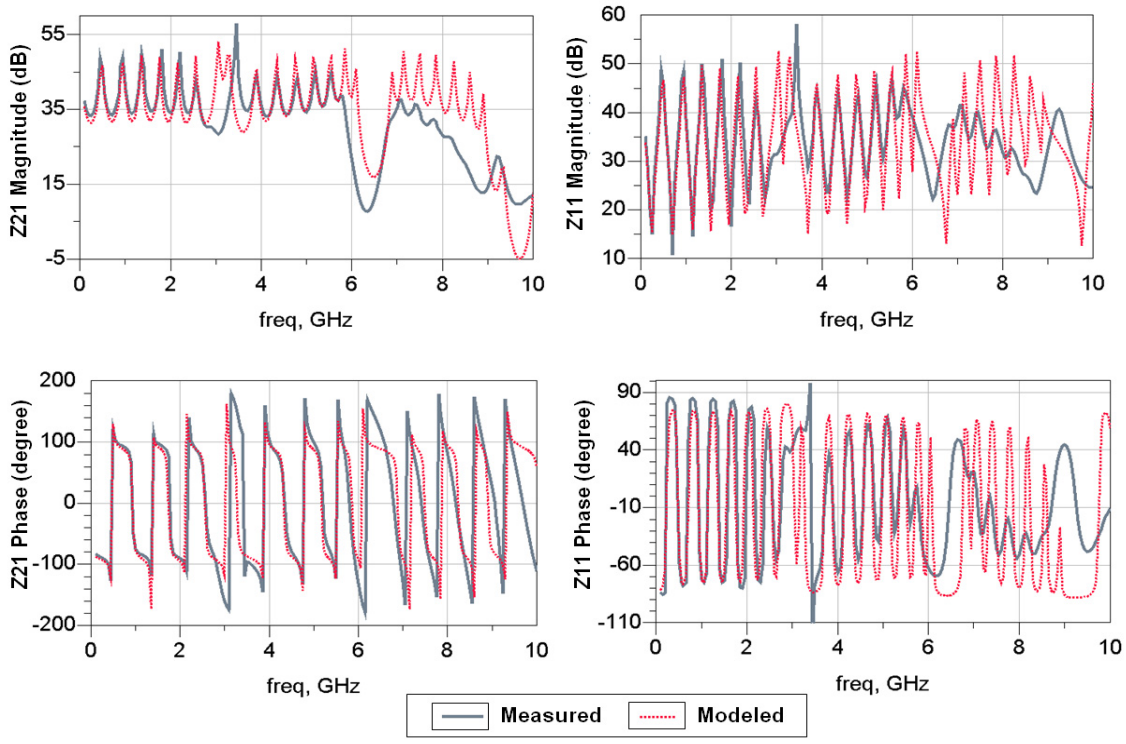



Figure 5.15. Predicted Z-parameter data of the 6-turn serpentine structure.

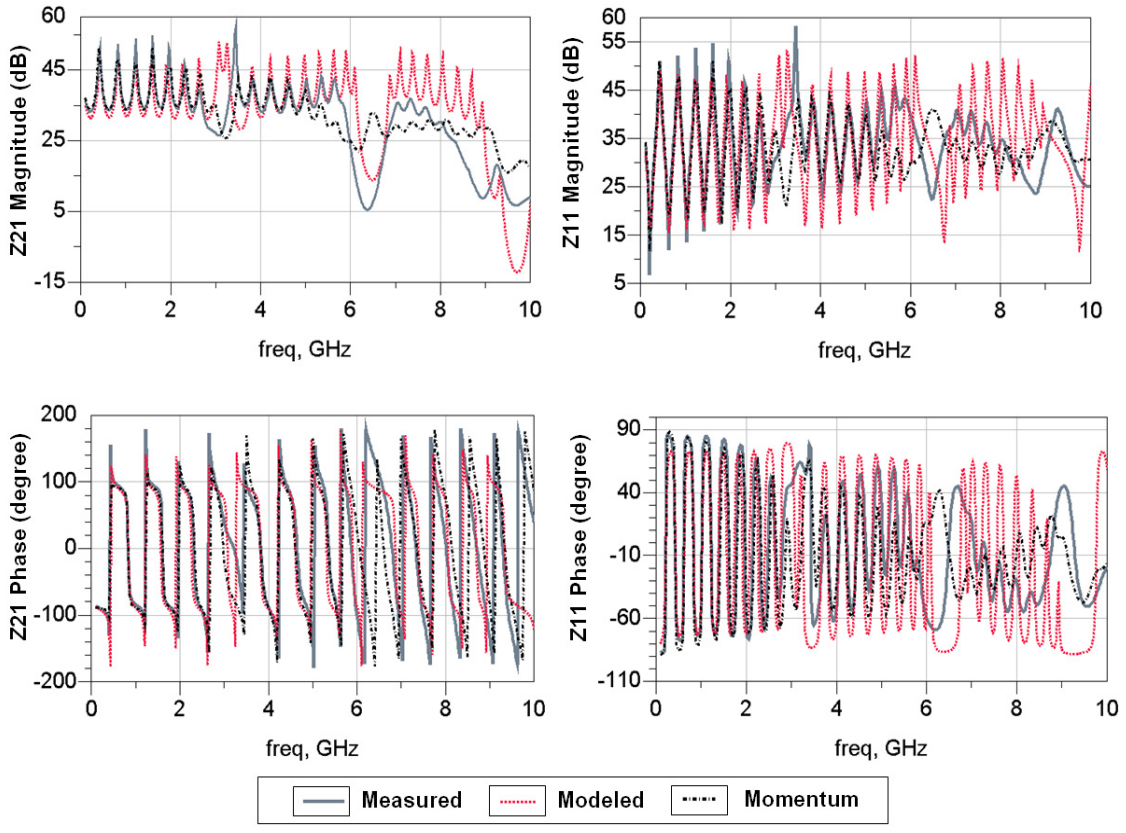
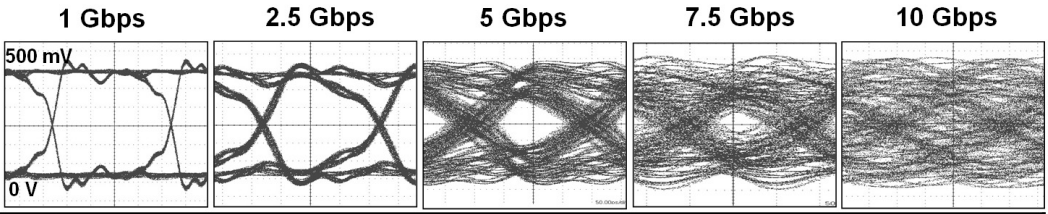


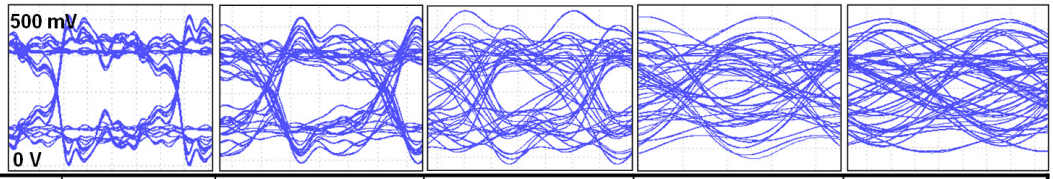

Figure 5.16. Predicted Z-parameter data of the 7-turn serpentine structure.

Along with the prediction of the frequency response, the time domain responses of the 7-turn serpentine structure are determined from the predictive model. As shown in Figure 5.17, the eye diagrams of the prediction have similar eye opening as those of the measurements. From these result, when utilizing the 7-turn serpentine structure demonstrated in this work for the interconnects on FR4 board, we can expect poor signal integrity at higher than 5 GHz frequency. Thus, we can avoid selecting this structure or co-design the system with compensation techniques such as the matching technique.




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 77.34 % | 70.37 % | 35.29 % | 13.79 % | 0 % |
| Jitter [UI] | 1.09 % | 7.66 % | 42.86 % | 62.96 % | 100 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 61.48 % | 51.82 % | 33.96 % | 9.68 % | 0 % |
| Jitter [UI] | 1.79 % | 13.70 % | 45.10 % | 67.24 % | 100 % |

(b) Simulated eye diagrams from the predictive model

Figure 5.17. Comparison of eye diagrams of the 7-turn serpentine structure.

As to the evaluation of the efficiency, simulation resource is defined as a UNIX computer of a 500 MHz Ultra SPARC IIi CPU with 2 G-byte memory. With this resource, simulation times of the momentum simulation and the prediction are compared according

to the number of turns of the serpentine structures as shown in Figure 5.18. In particular, for the 7-turn serpentine structure, the prediction completes in a few seconds while the momentum simulation takes more than a week to obtain the results. Even though the setup the momentum simulation can be modified to curtail its simulation time by sacrificing accuracy, it still is not competitive with the method proposed here. This is a strong motivation of this work in current digital system where the product lifetime is too short to wait for a long simulation time.

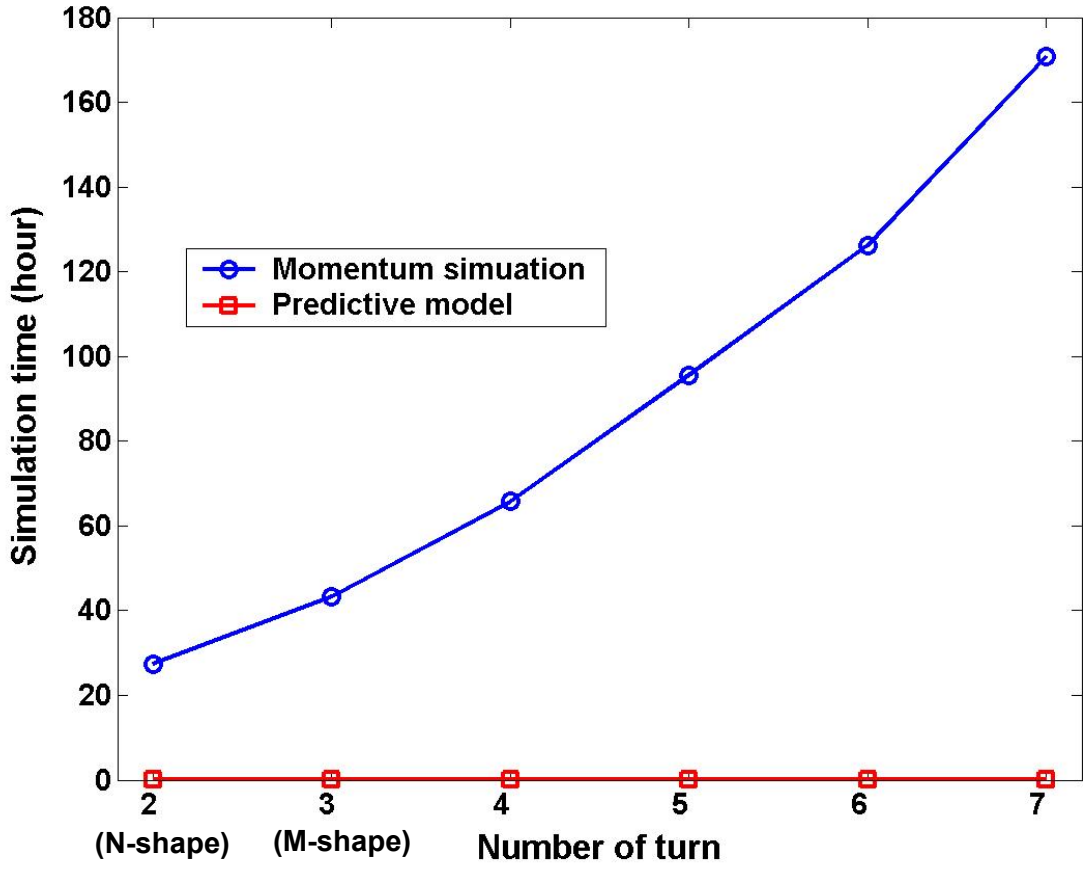



Figure 5.18. Comparison of simulation times regarding the number of turns of the serpentine structure.

## 5.5. Interpolation

This section describes the interpolation technique that can enhance the flexibility of the predictive model. Since EC-parameters of each building block have some relationship to the geometry of the building block, it may be possible to predict by interpolation a structure that lies between two other structures in terms of the geometrical variations. In this thesis work, as shown in Figure 5.19, we apply two interpolations with respect to the different widths and different spacings for predicting the N-shaped structure with 130-mil width and 130-mil spacing. These interpolations are performed with the linear interpolation equation. Herein, the interpolation between the structures with the different widths and the interpolation between the structures with the different spacing are referred to as the width-interpolation and spacing-interpolation, respectively.

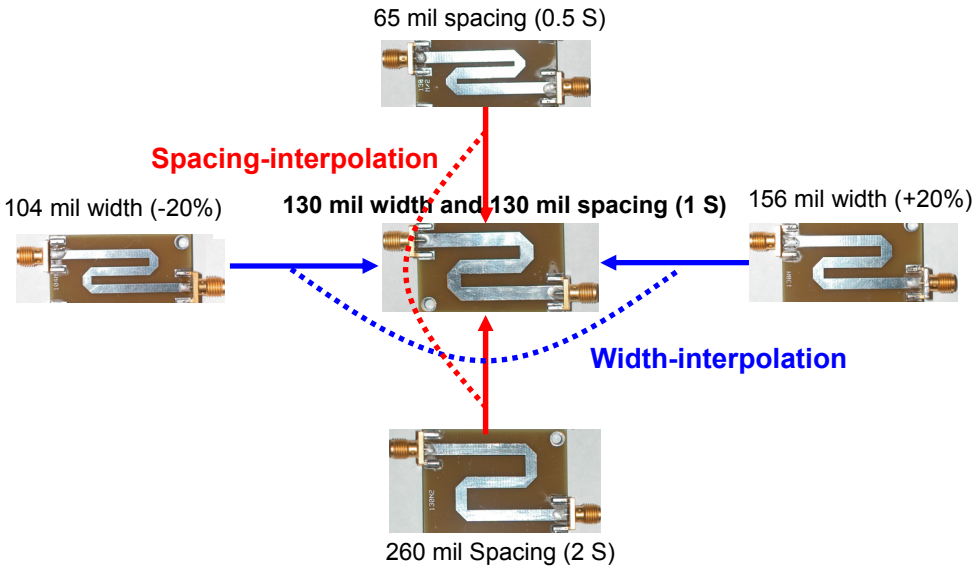



Figure 5.19. Interpolation diagram of the N-shaped serpentine.

### 5.5.1. Width-interpolation

For the width-interpolation, we use two N-shaped serpentine structures with widths (104 mils and 156 mils) deviated by ± 20 % from the 130-mil wide N-shaped structure. Prior to the optimization of these structures, it is necessary to observe the trend of the measured data of 104-mil, 130-mil and 156-mil wide serpentine structures. As shown in Figure 5.20, the comparison indicates that Z-parameter data of the N-shaped structures with the different widths seem to be shifted, and Z-parameter data of the 130-mil wide N-shaped serpentine structure are placed between that of the 104-mil wide and that of the 156-mil wide serpentine structure. This observation implies the possibility of this interpolation.

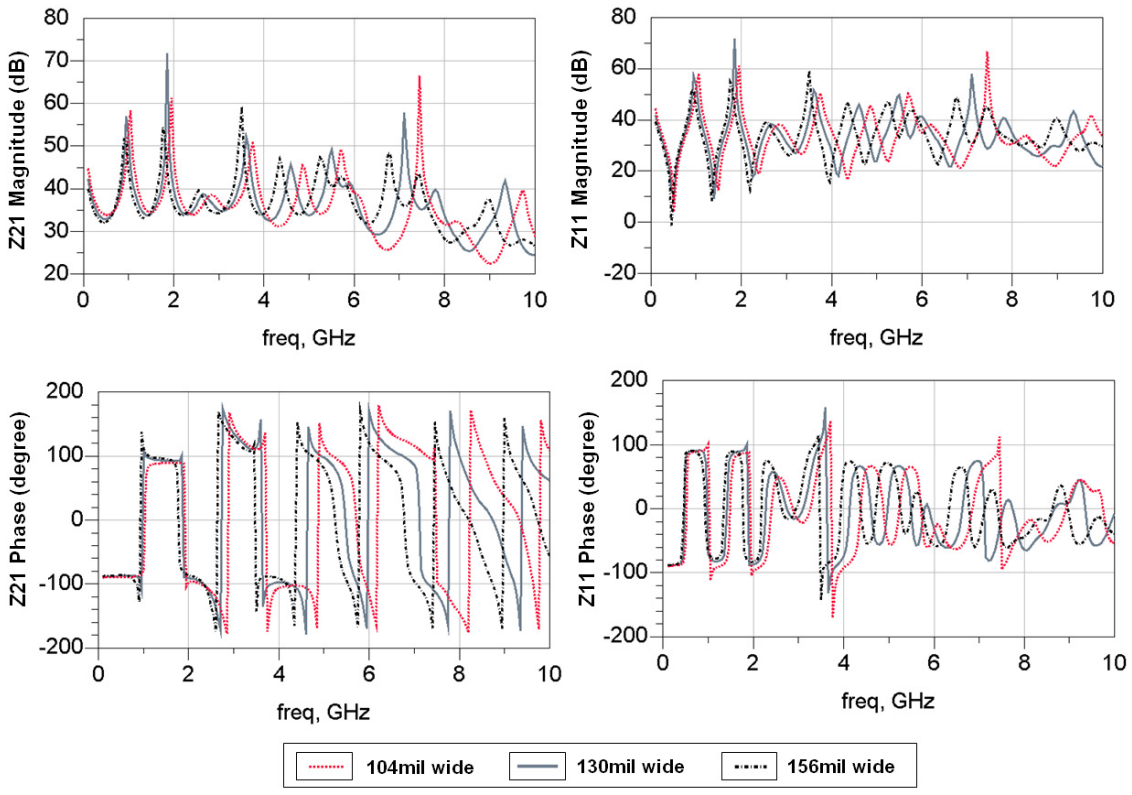



Figure 5.20. Comparison of the measured data of the N-shaped structures with three different widths.

Using the same optimization process described early in this chapter, 104-mil wide and 156-mil wide N-shaped serpentine structures are optimized to find sets of the EC-parameters for the width-interpolation. Figure 5.21 and Figure 5.22 show that the results of 104-mil wide and 156-mil wide serpentine structures have a good agreement with the measurements in a broad frequency range; accordingly, these structures have reasonable sets of the EC-parameters for the width-interpolation.

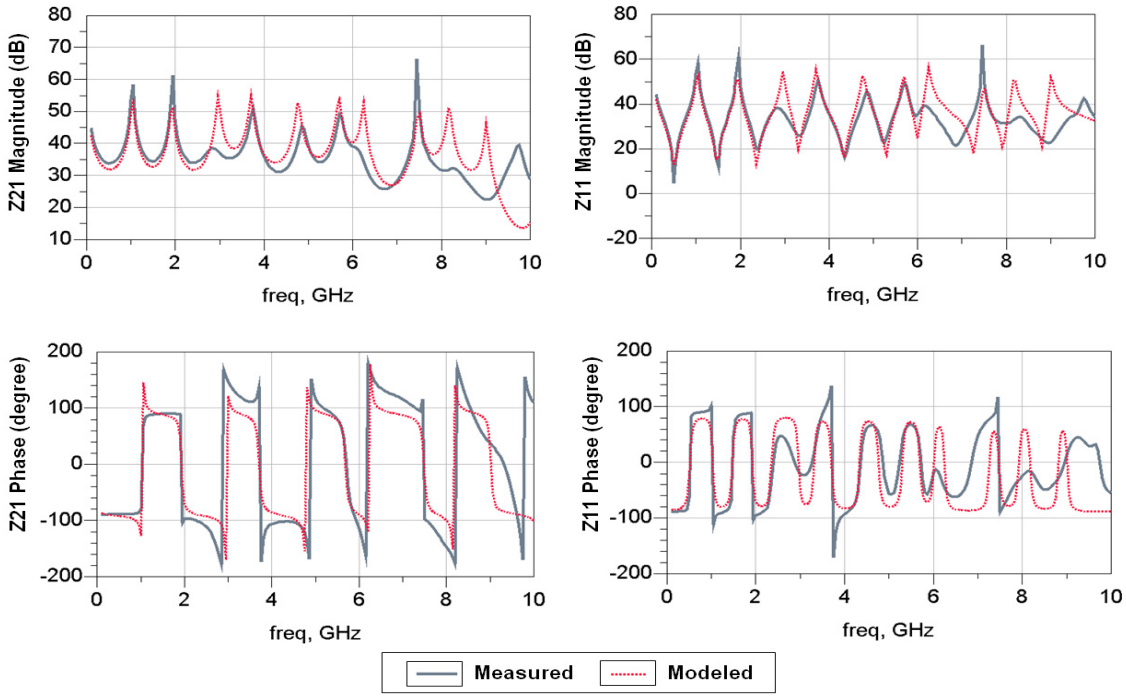



Figure 5.21. Optimized Z-parameter data of the 104-mil wide N-shaped serpentine structure.

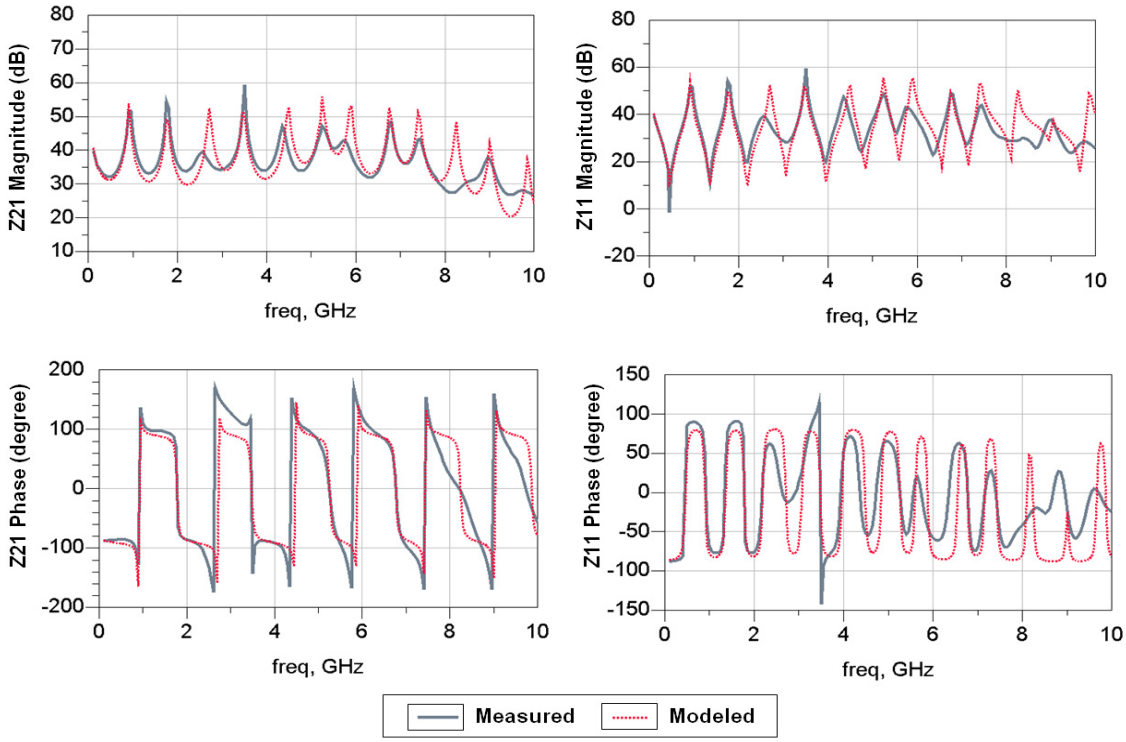



Figure 5.22. Optimized Z-parameter data of the 156-mil wide N-shaped serpentine structure.

With these optimized EC-parameters, EC-parameters of 130-mil wide N-shaped serpentine structure are interpolated to predict its frequency responses. The schematic for the width-interpolation are provided in Appendix B.4. As shown in Figure 5.23 and Figure 5.24, the results of the 130-mil wide N-shaped structure predicted by the width-interpolation have a good agreement with the measured data in the frequency and time domains. Furthermore, the results of the 130-mil wide M-shaped structure predicted with these interpolated EC-parameters have a good agreement with the measurement data, as shown in Figure 5.25 and Figure 5.26.

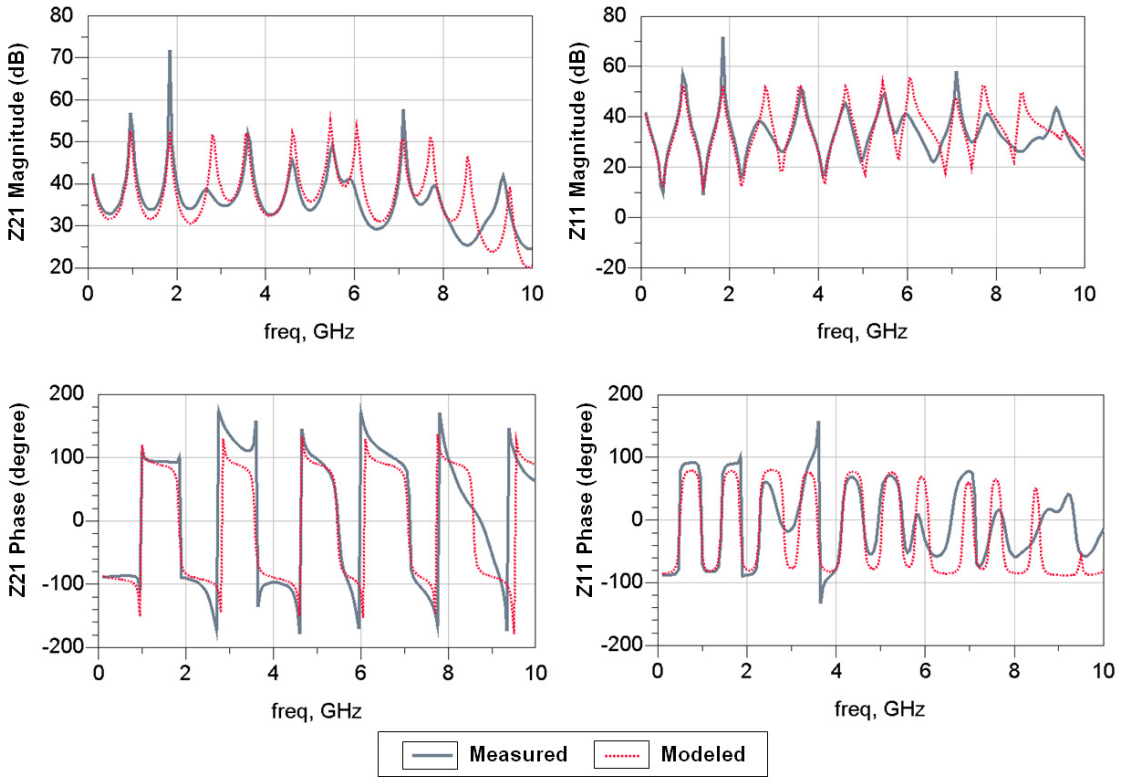
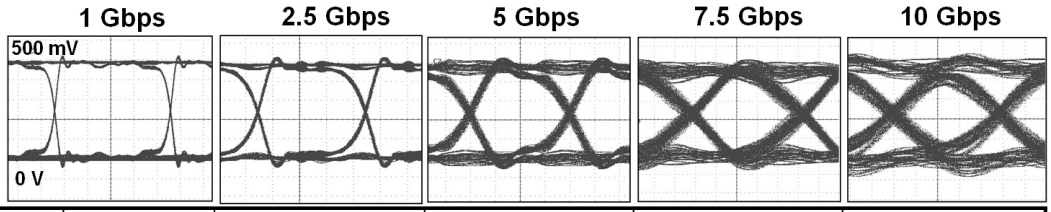
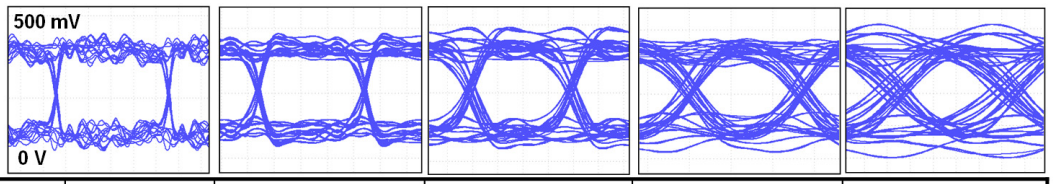



Figure 5.23. Predicted Z-parameter data of the 130-mil wide N-shaped serpentine structure by the width-interpolation.




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 82.08 % | 72.08 % | 68.18 % | 63.22 % | 45.56 % |
| Jitter [UI] | 1.12 % | 2.36 % | 10.50 % | 18.08 % | 23.72 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 73.91 % | 65.84 % | 63.91 % | 59.17 % | 43.45 % |
| Jitter [UI] | 1.87 % | 5.58 % | 12.40 % | 19.77 % | 30.91 % |

(b) Eye diagrams predicted by the width-interpolation

Figure 5.24. Eye diagram comparison of the 130-mil wide N-shaped serpentine structure.

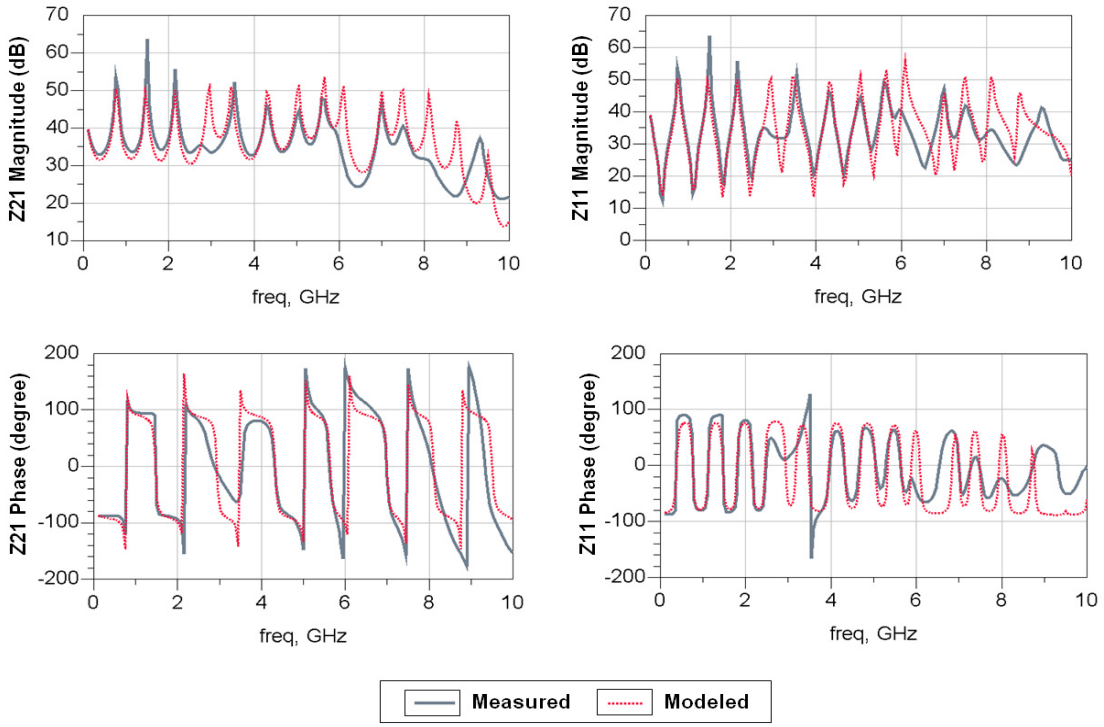
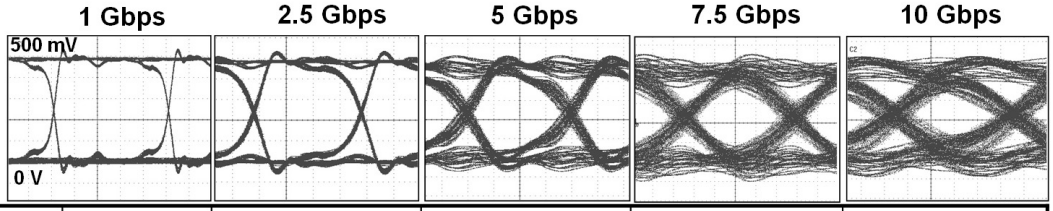
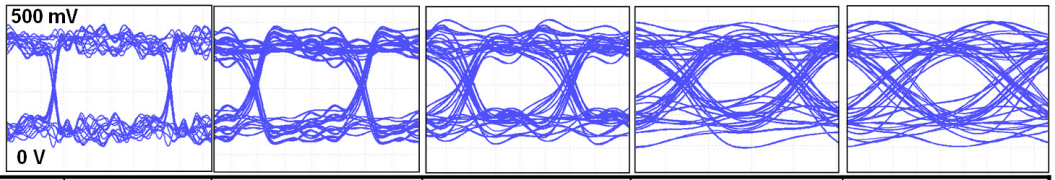



Figure 5.25. Z-parameter data of the 130-mil wide M-shaped serpentine structure predicted with the interpolated EC-parameters of the N-shaped serpentine structure by the width-interpolation.




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 81.13 % | 71.70 % | 60.77 % | 48.08 % | 35.38 % |
| Jitter [UI] | 1.27 % | 4.37 % | 16.33 % | 24.62 % | 32.14 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 71.17 % | 64.29 % | 56.05 % | 43.33 % | 35.56 % |
| Jitter [UI] | 1.95 % | 7.17 % | 17.92 % | 26.04 % | 35.02 % |

(b) Eye diagrams predicted with the interpolated parameters of the N-shaped serpentine structure by the width-interpolation.

Figure 5.26. Eye diagram comparison of the 130-mil wide M-shaped serpentine structure.

### 5.5.2. Spacing-interpolation

In the same manner as the width-interpolation, the spacing-interpolation is applied between two 130-mil wide N-shaped structures with 65-mil (0.5S) spacing and 260-mil (2S) spacing. As shown in Figure 5.27, the Z-parameter data of each structure seem to be irregular trends at first glance. The N-shaped serpentine structure with 0.5S spacing and that with 2S spacing are optimized for spacing-interpolation. These optimized results are reasonably useful for the spacing interpolation as shown in Figure 5.28 and Figure 5.29. With the optimized EC-parameters, the N-shaped serpentine structure with 1S spacing is predicted by the spacing interpolation using the schematic provided in Appendix B.5. Besides, the M-shaped serpentine structure with 1S spacing is predicted with these interpolated EC-parameters. According to the results of Figure 5.30, Figure 5.31, Figure 5.32 and Figure 5.33, we are convinced that the prediction by the spacing-interpolation has a good agreement with the measurements in the frequency and time domains.

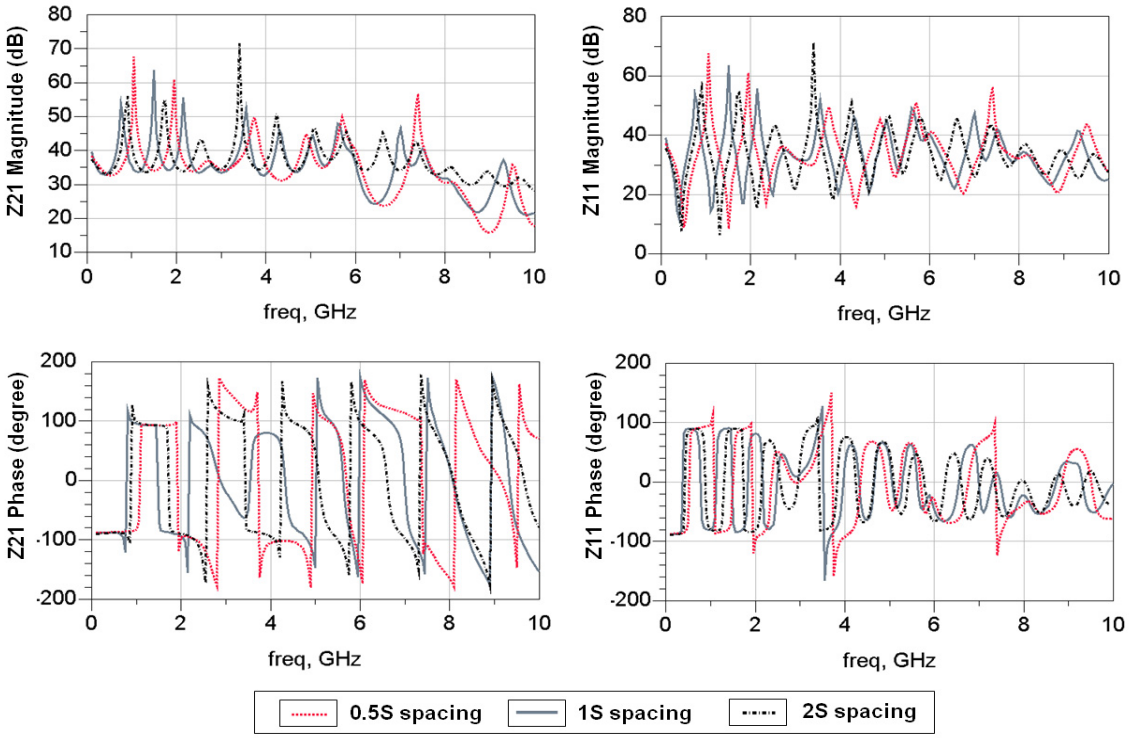



Figure 5.27. Comparison of the measured data of the N-shaped structure with three different spacings.

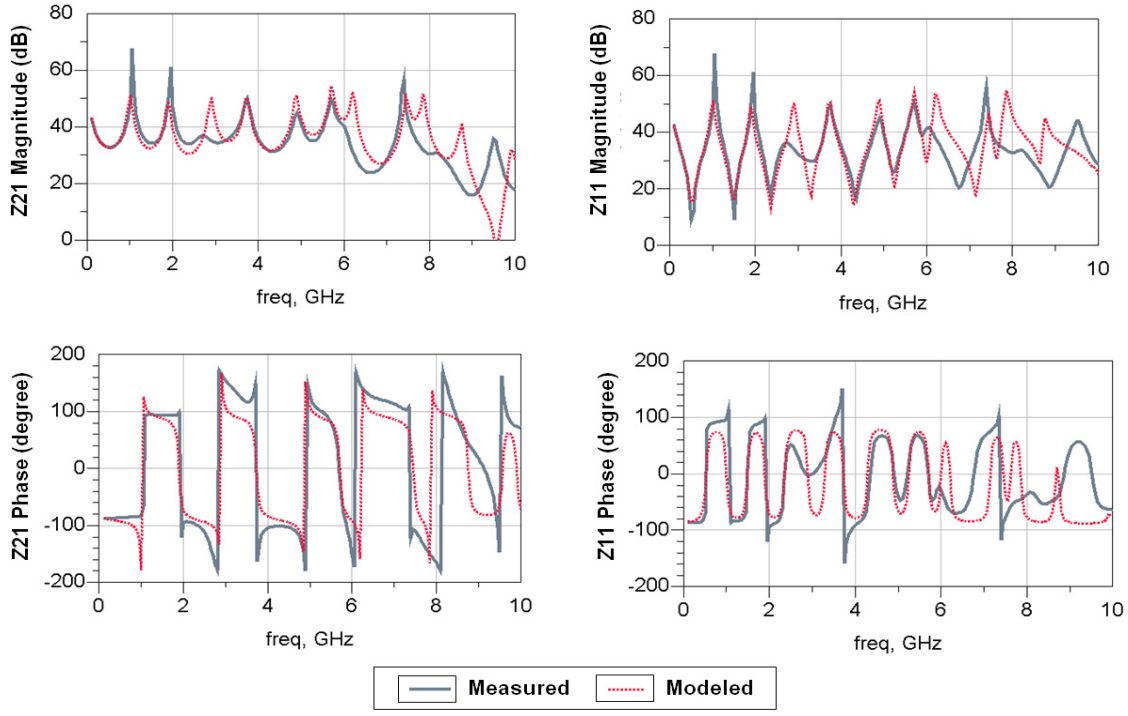



Figure 5.28. Optimized Z-parameter data of the N-shaped serpentine structure with 0.5S spacing.

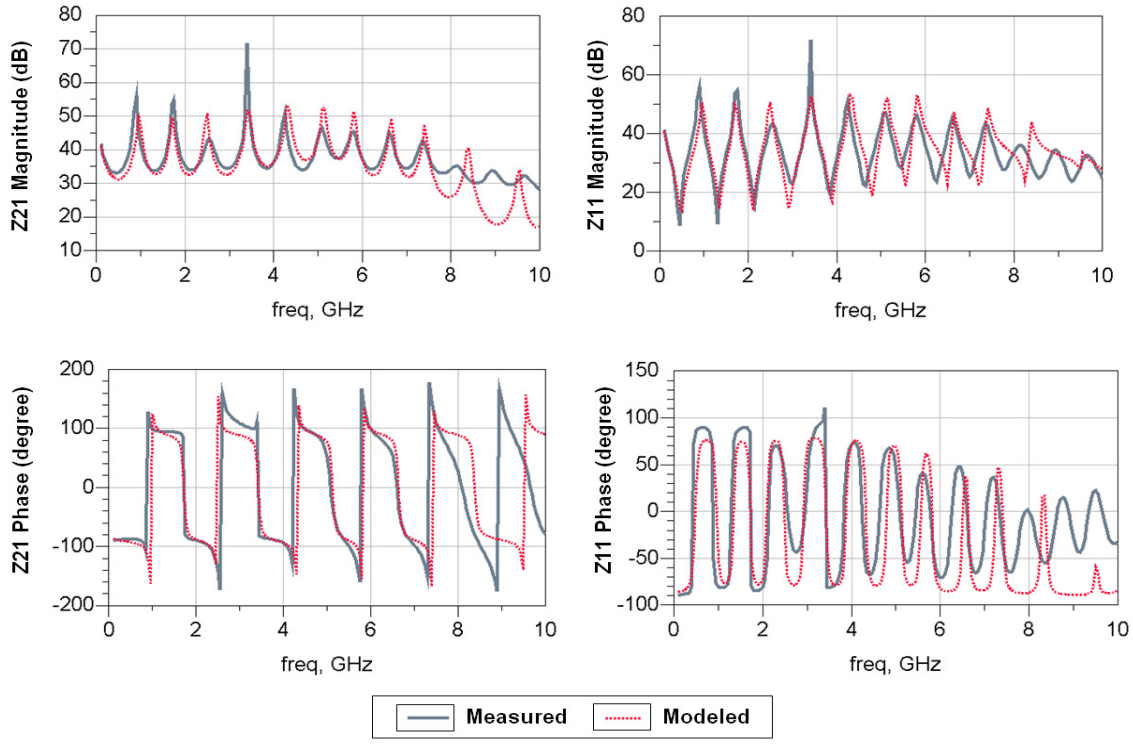



Figure 5.29. Optimized Z-parameter data of the N-shaped serpentine structure with 2S spacing.

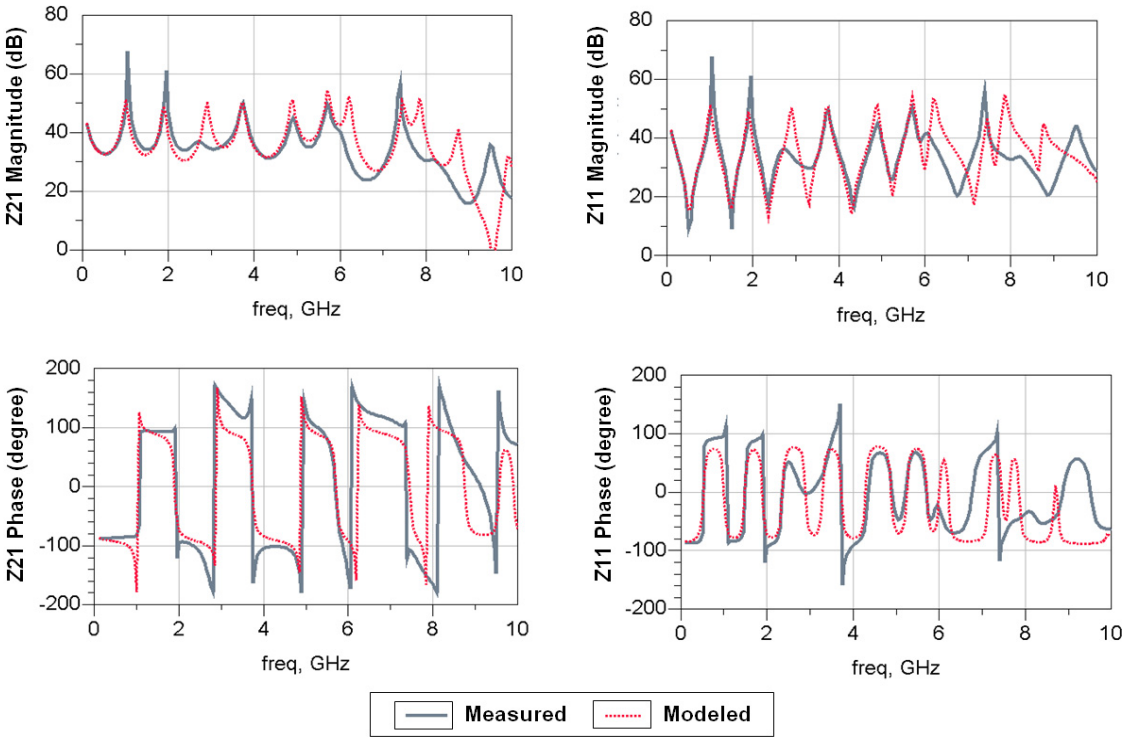
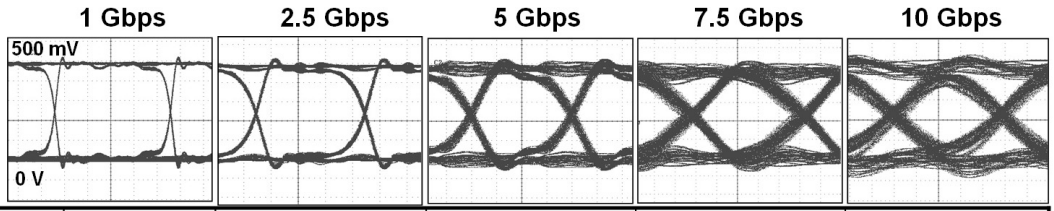
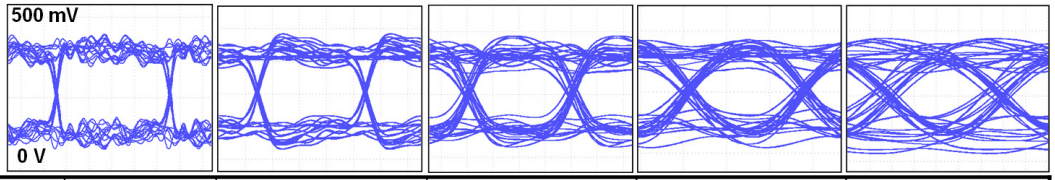



Figure 5.30. Predicted Z-parameter data of the N-shaped serpentine structure with 1S spacing by the spacing-interpolation.




| | | | | | |
|---|---|---|---|---|---|
| **Eye-opening** | 82.08 % | 72.08 % | 68.18 % | 63.22 % | 45.56 % |
| **Jitter [UI]** | 1.12 % | 2.36 % | 10.50 % | 18.08 % | 23.72 % |

(a) Measured eye diagrams




| | | | | | |
|---|---|---|---|---|---|
| **Eye-opening** | 73.33 % | 65.11 % | 61.70 % | 57.39 % | 42.86 % |
| **Jitter [UI]** | 1.92 % | 4.76 % | 13.11 % | 16.98 % | 23.81 % |

(b) Eye diagrams predicted by the spacing-interpolation

Figure 5.31. Eye diagram comparison of the N-shaped serpentine structure with 1S spacing.

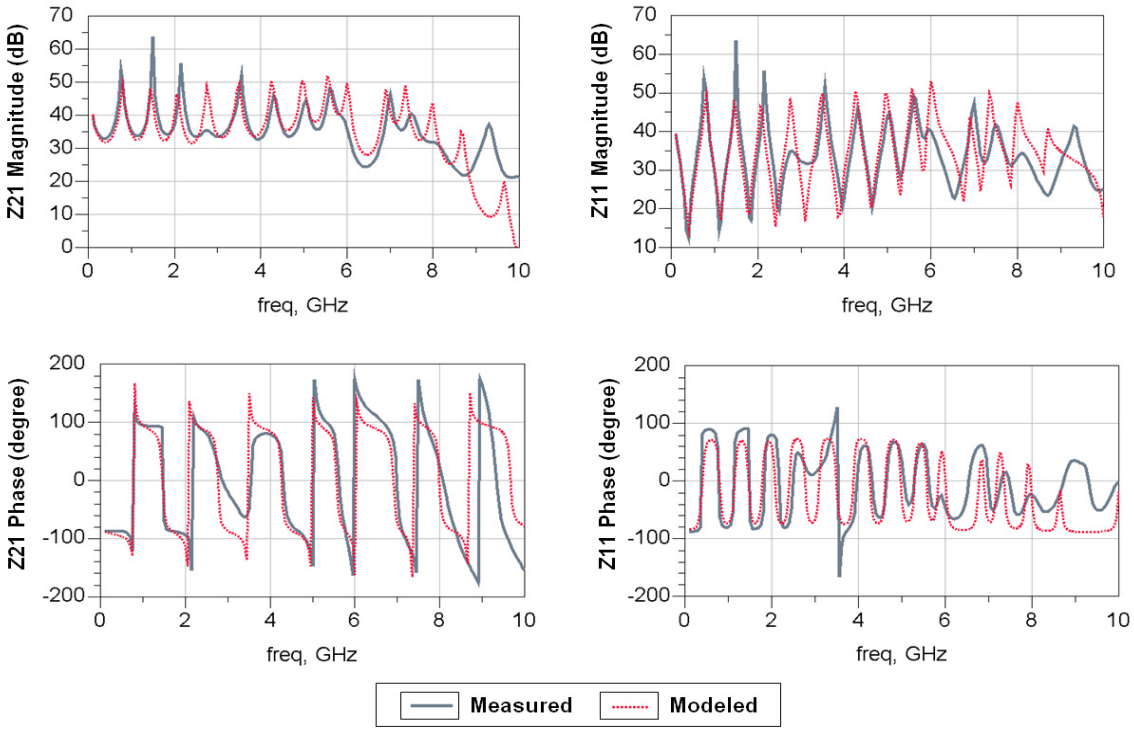
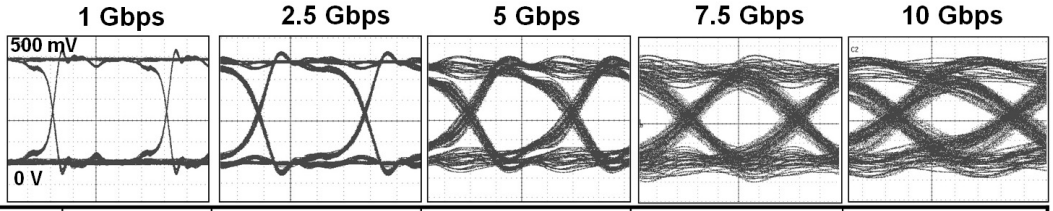
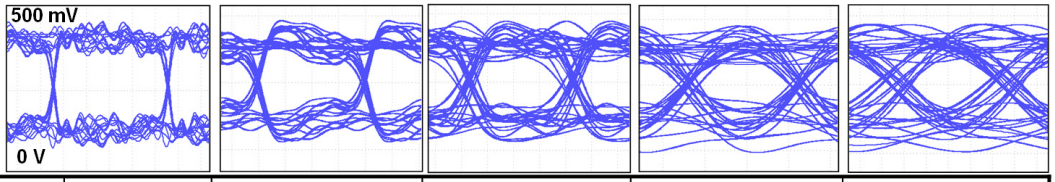



Figure 5.32. Z-parameter data of the M-shaped serpentine structure predicted with the interpolated EC-parameters of the N-shaped serpentine structure by the spacing-interpolation.




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 81.13 % | 71.70 % | 60.77 % | 48.08 % | 35.38 % |
| Jitter [UI] | 1.27 % | 4.37 % | 16.33 % | 24.62 % | 32.14 % |

(a) Measured eye diagrams




| | 1 Gbps | 2.5 Gbps | 5 Gbps | 7.5 Gbps | 10 Gbps |
|---|---|---|---|---|---|
| Eye-opening | 75.74 % | 60.24 % | 51.81 % | 47.92 % | 35.71 % |
| Jitter [UI] | 1.98 % | 7.14 % | 20.80 % | 21.89 % | 29.59 % |

(b) Eye diagrams predicted with the interpolated parameters of the N-shaped serpentine structure by the spacing-interpolation.

Figure 5.33. Eye diagram comparison of the M-shaped serpentine structure with 1S spacing.

## 5.6. Summary

In this chapter, a rapid, predictive (scalable) measurement-based method for high-frequency serpentine interconnects on low-cost FR4 board has been described. The structures of the predictive model have been designed and their measured data have been obtained after determining its building blocks. The equivalent circuit of each building block is derived from the PEEC model and then modified to incorporate the geometrical properties of the interconnect structure. The EC-parameters of each building block have been optimized such that they coincide with the measured data in their Z-parameter data.

The predictive model then has been applied to more scalable structures. The results from the prediction have been evaluated by comparing the predicted results, measured data, and the results of the momentum simulation from three perspectives: the Z-parameter data in the frequency domain, the eye diagrams in the time domain and the simulation time. The comparison results conclude that the method developed here is useful for prediction and efficiently applicable to model the serpentine structure on low-cost FR4 board whose electrical performance may be poor at high frequency.

In addition, the interpolations with respect to the width and spacing has been developed and demonstrated for their accuracy both in the frequency domain and in the time domain. These results show that these interpolations can be the applicable ways to improve the flexibility of the predictive model.

Considering model performance and complexity of the frequency response and geometry demonstrated in this chapter, we may infer that this predictive method can be applicable to other board level interconnect structures.

# CHAPTER VI

## CONCLUSION AND FUTURE WORK

### 6.1. Conclusion

As the demands for high data rates, miniaturization, and the system convergence on the electrical boards dramatically increase, an electrical board-level interconnect between systems seems to confront the limitations spoiling the signal integrity of the system. In the meantime, many researchers and developers managing the electrical board-level interconnects have endeavored to find breakthroughs to overcome these limitations.

In this dissertation, we have developed a rapid, predictive measurement-based PEEC model method for high-frequency interconnects on low-cost FR4 board. Experimentally, two case studies on straight microstrip lines and serpentine structures have been performed to illustrate the usefulness of the predictive modeling method. The efficiency and accuracy of the predictive modeling method have been compared with those of the ADS momentum simulation. Additionally, the width- and spacing-interpolations have been developed to improve the flexibility of the predictive modeling method. From the results, we can conclude that the predictive modeling method developed in this dissertation is efficiently applicable to design high frequency interconnects on low-cost FR4 board and has better performance than the momentum simulation. This suggests that the modeling method can be appropriate for industrial digital products that may require rapid design cycles.

## 6.2. Future Work

Based on the results of this thesis work, the following tasks are valuable to further improve the predictive measurement-based PEEC modeling method.

- **Automation of the process of the predictive modeling method:**

Customizing the whole process of the modeling method is important to make it useful for practical industrial designs. As for the predictive modeling method described in this dissertation, the steps after the calibration and measurement (see Figure 3.1) can be automated.

- **Via modeling using the measurement-based PEEC modeling method:**

The measurement-based PEEC modeling methodology may be applicable to other structures on low-cost FR4 board. A via structure may be a good candidate because it is one of the essential elements on electrical boards and has geometrical discontinuities that hamper signal integrity.

- **Optical interconnect modeling using the measurement-based PEEC modeling method:**

The interface between an optical device and an electrical system is a critical element for the signal integrity of optical embedded interconnects. Since characteristics of the interface are directly associated with fabrication of an optical device, the existing simulation tools cannot support interface modeling. Hence, the interface is a good candidate for the measurement-based PEEC modeling method. Signal conversion from an optical signal to an electrical signal can be measured by a light-wave component analyzer.

# APPENDIX A

# MEASURED DATA

## A.1. 130-mil wide N-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -2.231152E+01 | -1.377031E+02 | -8.364868E-02 | -3.702734E+01 |
| 1.793500E+08 | -2.162598E+01 | -1.436406E+02 | -9.627914E-02 | -4.208593E+01 |
| 2.287000E+08 | -2.090527E+01 | -1.505469E+02 | -1.119881E-01 | -4.797461E+01 |
| 2.780500E+08 | -2.017676E+01 | -1.583594E+02 | -1.259079E-01 | -5.470117E+01 |
| 3.274000E+08 | -1.944726E+01 | -1.672109E+02 | -1.447830E-01 | -6.226953E+01 |
| 3.767500E+08 | -1.872461E+01 | -1.770234E+02 | -1.632538E-01 | -7.065234E+01 |
| 4.261000E+08 | -1.804004E+01 | 1.721875E+02 | -1.841507E-01 | -7.987890E+01 |
| 4.754500E+08 | -1.761719E+01 | 1.614219E+02 | -2.010574E-01 | -8.910936E+01 |
| 5.248000E+08 | -1.742676E+01 | 1.507578E+02 | -2.192459E-01 | -9.834764E+01 |
| 5.741500E+08 | -1.741992E+01 | 1.400000E+02 | -2.406921E-01 | -1.075859E+02 |
| 6.235000E+08 | -1.760058E+01 | 1.292969E+02 | -2.423935E-01 | -1.168516E+02 |
| 6.728500E+08 | -1.796777E+01 | 1.186953E+02 | -2.566833E-01 | -1.261562E+02 |
| 7.222000E+08 | -1.855176E+01 | 1.083242E+02 | -2.639923E-01 | -1.354844E+02 |
| 7.715500E+08 | -1.940722E+01 | 9.824999E+01 | -2.721252E-01 | -1.448672E+02 |
| 8.209000E+08 | -2.056152E+01 | 8.897655E+01 | -2.796021E-01 | -1.542734E+02 |
| 8.702500E+08 | -2.220508E+01 | 8.220703E+01 | -2.839203E-01 | -1.637422E+02 |
| 9.196000E+08 | -2.398535E+01 | 8.030077E+01 | -2.897034E-01 | -1.732656E+02 |
| 9.689500E+08 | -2.523046E+01 | 8.144922E+01 | -2.960052E-01 | 1.771406E+02 |
| 1.018300E+09 | -2.613379E+01 | 8.419922E+01 | -3.109741E-01 | 1.675313E+02 |
| 1.067650E+09 | -2.677637E+01 | 8.714453E+01 | -3.199310E-01 | 1.578750E+02 |
| 1.117000E+09 | -2.714746E+01 | 9.038671E+01 | -3.267822E-01 | 1.481641E+02 |
| 1.166350E+09 | -2.734082E+01 | 9.388281E+01 | -3.491974E-01 | 1.384219E+02 |
| 1.215700E+09 | -2.733301E+01 | 9.706640E+01 | -3.615112E-01 | 1.286406E+02 |
| 1.265050E+09 | -2.708887E+01 | 1.004570E+02 | -3.755646E-01 | 1.188047E+02 |
| 1.314400E+09 | -2.661523E+01 | 1.036445E+02 | -3.908539E-01 | 1.089492E+02 |
| 1.363750E+09 | -2.581543E+01 | 1.059023E+02 | -4.128571E-01 | 9.902733E+01 |
| 1.413100E+09 | -2.453516E+01 | 1.059570E+02 | -4.337616E-01 | 8.905859E+01 |
| 1.462450E+09 | -2.313183E+01 | 1.011172E+02 | -4.555359E-01 | 7.905859E+01 |
| 1.511800E+09 | -2.223535E+01 | 9.333984E+01 | -4.769745E-01 | 6.899219E+01 |
| 1.561150E+09 | -2.169140E+01 | 8.394922E+01 | -4.951782E-01 | 5.889648E+01 |
| 1.610500E+09 | -2.139355E+01 | 7.426562E+01 | -5.194702E-01 | 4.876953E+01 |
| 1.659850E+09 | -2.137793E+01 | 6.451172E+01 | -5.461731E-01 | 3.862500E+01 |
| 1.709200E+09 | -2.142578E+01 | 5.477148E+01 | -5.684509E-01 | 2.843945E+01 |
| 1.758550E+09 | -2.154297E+01 | 4.526953E+01 | -5.926819E-01 | 1.817676E+01 |
| 1.807900E+09 | -2.166308E+01 | 3.491015E+01 | -6.184082E-01 | 7.893555E+00 |
| 1.857250E+09 | -2.174805E+01 | 2.436328E+01 | -6.510315E-01 | -2.463745E+00 |
| 1.906600E+09 | -2.183594E+01 | 1.312451E+01 | -6.893005E-01 | -1.285303E+01 |
| 1.955950E+09 | -2.181738E+01 | 1.246948E+00 | -7.257996E-01 | -2.321289E+01 |
| 2.005300E+09 | -2.180371E+01 | -1.056885E+01 | -7.637634E-01 | -3.358984E+01 |

| | | | | |
|---|---|---|---|---|
| 2.054650E+09 | -2.160351E+01 | -2.288672E+01 | -8.025208E-01 | -4.391797E+01 |
| 2.104000E+09 | -2.123828E+01 | -3.515039E+01 | -8.365479E-01 | -5.436913E+01 |
| 2.153350E+09 | -2.071484E+01 | -4.760156E+01 | -8.634338E-01 | -6.477734E+01 |
| 2.202700E+09 | -1.995019E+01 | -6.052929E+01 | -9.026489E-01 | -7.523046E+01 |
| 2.252050E+09 | -1.910058E+01 | -7.389843E+01 | -9.531250E-01 | -8.582811E+01 |
| 2.301400E+09 | -1.816015E+01 | -8.769531E+01 | -1.004150E+00 | -9.631639E+01 |
| 2.350750E+09 | -1.720019E+01 | -1.012461E+02 | -1.065918E+00 | -1.067539E+02 |
| 2.400100E+09 | -1.621680E+01 | -1.147461E+02 | -1.120972E+00 | -1.171836E+02 |
| 2.449450E+09 | -1.519922E+01 | -1.275742E+02 | -1.167358E+00 | -1.275430E+02 |
| 2.498800E+09 | -1.422461E+01 | -1.400156E+02 | -1.228271E+00 | -1.378828E+02 |
| 2.548150E+09 | -1.315381E+01 | -1.525469E+02 | -1.286926E+00 | -1.482734E+02 |
| 2.597500E+09 | -1.221240E+01 | -1.647266E+02 | -1.378662E+00 | -1.586250E+02 |
| 2.646850E+09 | -1.135352E+01 | -1.770391E+02 | -1.456787E+00 | -1.689609E+02 |
| 2.696200E+09 | -1.057520E+01 | 1.709609E+02 | -1.573914E+00 | -1.790000E+02 |
| 2.745550E+09 | -9.929199E+00 | 1.592109E+02 | -1.678101E+00 | 1.707813E+02 |
| 2.794900E+09 | -9.354004E+00 | 1.477109E+02 | -1.762939E+00 | 1.611094E+02 |
| 2.844250E+09 | -8.873535E+00 | 1.366641E+02 | -1.878784E+00 | 1.513281E+02 |
| 2.893600E+09 | -8.448242E+00 | 1.258945E+02 | -1.970642E+00 | 1.416875E+02 |
| 2.942950E+09 | -8.061035E+00 | 1.152656E+02 | -2.073364E+00 | 1.321094E+02 |
| 2.992300E+09 | -7.744629E+00 | 1.046836E+02 | -2.160645E+00 | 1.226523E+02 |
| 3.041650E+09 | -7.489502E+00 | 9.415234E+01 | -2.249634E+00 | 1.134180E+02 |
| 3.091000E+09 | -7.327881E+00 | 8.387499E+01 | -2.344849E+00 | 1.043711E+02 |
| 3.140350E+09 | -7.228271E+00 | 7.371484E+01 | -2.377808E+00 | 9.518358E+01 |
| 3.189700E+09 | -7.180420E+00 | 6.387695E+01 | -2.408325E+00 | 8.652344E+01 |
| 3.239050E+09 | -7.190186E+00 | 5.405273E+01 | -2.431519E+00 | 7.753906E+01 |
| 3.288400E+09 | -7.226807E+00 | 4.434766E+01 | -2.412354E+00 | 6.880077E+01 |
| 3.337750E+09 | -7.327881E+00 | 3.465625E+01 | -2.393433E+00 | 5.981445E+01 |
| 3.387100E+09 | -7.478027E+00 | 2.495605E+01 | -2.317505E+00 | 5.104687E+01 |
| 3.436450E+09 | -7.697998E+00 | 1.531494E+01 | -2.276489E+00 | 4.213476E+01 |
| 3.485800E+09 | -7.980713E+00 | 5.598877E+00 | -2.178833E+00 | 3.309765E+01 |
| 3.535150E+09 | -8.322266E+00 | -3.879639E+00 | -2.098755E+00 | 2.412109E+01 |
| 3.584500E+09 | -8.718262E+00 | -1.329639E+01 | -2.008545E+00 | 1.485742E+01 |
| 3.633850E+09 | -9.134766E+00 | -2.287988E+01 | -1.898987E+00 | 5.498535E+00 |
| 3.683200E+09 | -9.618652E+00 | -3.241015E+01 | -1.799866E+00 | -3.712036E+00 |
| 3.732550E+09 | -1.015771E+01 | -4.229688E+01 | -1.730957E+00 | -1.326904E+01 |
| 3.781900E+09 | -1.071777E+01 | -5.216601E+01 | -1.631714E+00 | -2.290820E+01 |
| 3.831250E+09 | -1.136279E+01 | -6.237890E+01 | -1.559265E+00 | -3.252734E+01 |
| 3.880600E+09 | -1.200244E+01 | -7.273438E+01 | -1.503113E+00 | -4.219140E+01 |
| 3.929950E+09 | -1.268555E+01 | -8.320313E+01 | -1.476379E+00 | -5.205468E+01 |
| 3.979300E+09 | -1.336816E+01 | -9.437891E+01 | -1.422607E+00 | -6.193164E+01 |
| 4.028650E+09 | -1.400488E+01 | -1.057578E+02 | -1.408264E+00 | -7.167969E+01 |
| 4.078000E+09 | -1.463965E+01 | -1.177344E+02 | -1.402405E+00 | -8.158983E+01 |
| 4.127350E+09 | -1.520166E+01 | -1.302109E+02 | -1.393311E+00 | -9.148046E+01 |
| 4.176700E+09 | -1.573584E+01 | -1.430156E+02 | -1.393005E+00 | -1.013984E+02 |
| 4.226050E+09 | -1.618457E+01 | -1.563516E+02 | -1.416504E+00 | -1.113555E+02 |
| 4.275400E+09 | -1.654980E+01 | -1.696953E+02 | -1.434631E+00 | -1.213711E+02 |
| 4.324750E+09 | -1.685742E+01 | 1.765859E+02 | -1.458557E+00 | -1.313906E+02 |
| 4.374100E+09 | -1.706347E+01 | 1.630078E+02 | -1.492065E+00 | -1.414141E+02 |
| 4.423450E+09 | -1.725293E+01 | 1.491953E+02 | -1.531799E+00 | -1.515625E+02 |

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|---|---|---|---|---|
| 4.472800E+09 | -1.740039E+01 | 1.354219E+02 | -1.569580E+00 | -1.617500E+02 |
| 4.522150E+09 | -1.758496E+01 | 1.223789E+02 | -1.621948E+00 | -1.719531E+02 |
| 4.571500E+09 | -1.780762E+01 | 1.096055E+02 | -1.676636E+00 | 1.777500E+02 |
| 4.620850E+09 | -1.811230E+01 | 9.807421E+01 | -1.725464E+00 | 1.673281E+02 |
| 4.670200E+09 | -1.864941E+01 | 8.743359E+01 | -1.783569E+00 | 1.568438E+02 |
| 4.719550E+09 | -1.935644E+01 | 7.858593E+01 | -1.849060E+00 | 1.462188E+02 |
| 4.768900E+09 | -2.002344E+01 | 7.460938E+01 | -1.922791E+00 | 1.354687E+02 |
| 4.818250E+09 | -2.046875E+01 | 7.301562E+01 | -2.001465E+00 | 1.245820E+02 |
| 4.867600E+09 | -2.053906E+01 | 7.255859E+01 | -2.091797E+00 | 1.136484E+02 |
| 4.916950E+09 | -2.041992E+01 | 7.299218E+01 | -2.201416E+00 | 1.025547E+02 |
| 4.966300E+09 | -2.008691E+01 | 7.395312E+01 | -2.314941E+00 | 9.133593E+01 |
| 5.015650E+09 | -1.952832E+01 | 7.509375E+01 | -2.442627E+00 | 8.005077E+01 |
| 5.065000E+09 | -1.876465E+01 | 7.620312E+01 | -2.588013E+00 | 6.864062E+01 |
| 5.114350E+09 | -1.784180E+01 | 7.720312E+01 | -2.758911E+00 | 5.715820E+01 |
| 5.163700E+09 | -1.666992E+01 | 7.742578E+01 | -2.946289E+00 | 4.562304E+01 |
| 5.213050E+09 | -1.520898E+01 | 7.713672E+01 | -3.157837E+00 | 3.410937E+01 |
| 5.262400E+09 | -1.349854E+01 | 7.542578E+01 | -3.392578E+00 | 2.263574E+01 |
| 5.311750E+09 | -1.179346E+01 | 6.921093E+01 | -3.634766E+00 | 1.126367E+01 |
| 5.361100E+09 | -1.027344E+01 | 6.094727E+01 | -3.895386E+00 | -7.278442E-02 |
| 5.410450E+09 | -9.102051E+00 | 5.193359E+01 | -4.138184E+00 | -1.119678E+01 |
| 5.459800E+09 | -8.100586E+00 | 4.217578E+01 | -4.404297E+00 | -2.209277E+01 |
| 5.509150E+09 | -7.282715E+00 | 3.230859E+01 | -4.658936E+00 | -3.294922E+01 |
| 5.558500E+09 | -6.631836E+00 | 2.237500E+01 | -4.896240E+00 | -4.358984E+01 |
| 5.607850E+09 | -6.089355E+00 | 1.255859E+01 | -5.118408E+00 | -5.398828E+01 |
| 5.657200E+09 | -5.669922E+00 | 2.907227E+00 | -5.319092E+00 | -6.423046E+01 |
| 5.706550E+09 | -5.351563E+00 | -6.694824E+00 | -5.482422E+00 | -7.432422E+01 |
| 5.755900E+09 | -5.111816E+00 | -1.611230E+01 | -5.592773E+00 | -8.433203E+01 |
| 5.805250E+09 | -4.941895E+00 | -2.547070E+01 | -5.679688E+00 | -9.403515E+01 |
| 5.854600E+09 | -4.825684E+00 | -3.465039E+01 | -5.735352E+00 | -1.038984E+02 |
| 5.903950E+09 | -4.783203E+00 | -4.390429E+01 | -5.724121E+00 | -1.136758E+02 |
| 5.953300E+09 | -4.790283E+00 | -5.319336E+01 | -5.705078E+00 | -1.234336E+02 |
| 6.002650E+09 | -4.850098E+00 | -6.237499E+01 | -5.635742E+00 | -1.333984E+02 |
| 6.052000E+09 | -4.962402E+00 | -7.167969E+01 | -5.533203E+00 | -1.432969E+02 |
| 6.101350E+09 | -5.120850E+00 | -8.103516E+01 | -5.417725E+00 | -1.532500E+02 |
| 6.150700E+09 | -5.347656E+00 | -9.064844E+01 | -5.267822E+00 | -1.633750E+02 |
| 6.200050E+09 | -5.606201E+00 | -1.004726E+02 | -5.112793E+00 | -1.735781E+02 |
| 6.249400E+09 | -5.921143E+00 | -1.104609E+02 | -4.952637E+00 | 1.760469E+02 |
| 6.298750E+09 | -6.282471E+00 | -1.208320E+02 | -4.790527E+00 | 1.657187E+02 |
| 6.348100E+09 | -6.685303E+00 | -1.314062E+02 | -4.637207E+00 | 1.550547E+02 |
| 6.397450E+09 | -7.155029E+00 | -1.425313E+02 | -4.460938E+00 | 1.444375E+02 |
| 6.446800E+09 | -7.633301E+00 | -1.541953E+02 | -4.326904E+00 | 1.338203E+02 |
| 6.496150E+09 | -8.155273E+00 | -1.662500E+02 | -4.192383E+00 | 1.230547E+02 |
| 6.545500E+09 | -8.686035E+00 | -1.790547E+02 | -4.074463E+00 | 1.122852E+02 |
| 6.594850E+09 | -9.179199E+00 | 1.677891E+02 | -3.966919E+00 | 1.015430E+02 |
| 6.644200E+09 | -9.649414E+00 | 1.539141E+02 | -3.878174E+00 | 9.070313E+01 |
| 6.693550E+09 | -1.001611E+01 | 1.396172E+02 | -3.816406E+00 | 7.994922E+01 |
| 6.742900E+09 | -1.032910E+01 | 1.249687E+02 | -3.755859E+00 | 6.912890E+01 |
| 6.792250E+09 | -1.055420E+01 | 1.099141E+02 | -3.709961E+00 | 5.848046E+01 |
| 6.841600E+09 | -1.069385E+01 | 9.486328E+01 | -3.697021E+00 | 4.771484E+01 |

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|---|---|---|---|---|
| 6.890950E+09 | -1.073340E+01 | 7.966797E+01 | -3.653442E+00 | 3.702539E+01 |
| 6.940300E+09 | -1.067139E+01 | 6.487499E+01 | -3.664307E+00 | 2.651660E+01 |
| 6.989650E+09 | -1.055127E+01 | 5.032421E+01 | -3.666992E+00 | 1.583789E+01 |
| 7.039000E+09 | -1.033203E+01 | 3.614062E+01 | -3.674683E+00 | 5.196533E+00 |
| 7.088350E+09 | -1.007959E+01 | 2.258789E+01 | -3.683838E+00 | -5.383301E+00 |
| 7.137700E+09 | -9.812988E+00 | 9.368164E+00 | -3.725464E+00 | -1.584814E+01 |
| 7.187050E+09 | -9.547363E+00 | -2.958130E+00 | -3.773926E+00 | -2.640429E+01 |
| 7.236400E+09 | -9.348145E+00 | -1.479883E+01 | -3.781738E+00 | -3.710742E+01 |
| 7.285750E+09 | -9.179688E+00 | -2.592578E+01 | -3.809326E+00 | -4.735156E+01 |
| 7.335100E+09 | -9.127441E+00 | -3.619336E+01 | -3.888306E+00 | -5.806054E+01 |
| 7.384450E+09 | -9.155273E+00 | -4.608398E+01 | -3.894287E+00 | -6.878906E+01 |
| 7.433800E+09 | -9.300781E+00 | -5.491211E+01 | -3.951172E+00 | -7.930078E+01 |
| 7.483150E+09 | -9.573730E+00 | -6.282227E+01 | -3.996216E+00 | -9.019140E+01 |
| 7.532500E+09 | -9.921387E+00 | -6.937500E+01 | -4.037354E+00 | -1.010781E+02 |
| 7.581850E+09 | -1.035059E+01 | -7.438671E+01 | -4.085938E+00 | -1.120000E+02 |
| 7.631200E+09 | -1.070264E+01 | -7.801562E+01 | -4.154785E+00 | -1.231172E+02 |
| 7.680550E+09 | -1.095947E+01 | -8.029688E+01 | -4.221436E+00 | -1.345859E+02 |
| 7.729900E+09 | -1.110205E+01 | -8.183203E+01 | -4.276123E+00 | -1.460312E+02 |
| 7.779250E+09 | -1.109326E+01 | -8.283203E+01 | -4.447998E+00 | -1.574687E+02 |
| 7.828600E+09 | -1.097656E+01 | -8.359375E+01 | -4.587402E+00 | -1.697734E+02 |
| 7.877950E+09 | -1.070020E+01 | -8.447266E+01 | -4.725830E+00 | 1.787812E+02 |
| 7.927300E+09 | -1.030273E+01 | -8.504686E+01 | -4.974365E+00 | 1.668047E+02 |
| 7.976650E+09 | -9.805664E+00 | -8.624609E+01 | -5.230957E+00 | 1.549297E+02 |
| 8.026000E+09 | -9.152344E+00 | -8.814453E+01 | -5.509766E+00 | 1.432969E+02 |
| 8.075350E+09 | -8.419922E+00 | -9.076172E+01 | -5.823730E+00 | 1.319219E+02 |
| 8.124700E+09 | -7.634766E+00 | -9.480860E+01 | -6.147705E+00 | 1.204531E+02 |
| 8.174050E+09 | -6.911621E+00 | -9.998827E+01 | -6.497070E+00 | 1.096211E+02 |
| 8.223400E+09 | -6.299316E+00 | -1.062109E+02 | -6.797363E+00 | 9.863670E+01 |
| 8.272750E+09 | -5.782715E+00 | -1.132187E+02 | -7.116211E+00 | 8.832811E+01 |
| 8.322100E+09 | -5.417725E+00 | -1.203906E+02 | -7.343506E+00 | 7.773828E+01 |
| 8.371450E+09 | -5.171631E+00 | -1.280391E+02 | -7.583984E+00 | 6.819921E+01 |
| 8.420800E+09 | -5.011719E+00 | -1.356875E+02 | -7.753418E+00 | 5.760937E+01 |
| 8.470150E+09 | -4.973389E+00 | -1.436328E+02 | -7.822510E+00 | 4.811913E+01 |
| 8.519500E+09 | -5.004395E+00 | -1.516953E+02 | -7.860840E+00 | 3.797852E+01 |
| 8.568850E+09 | -5.151367E+00 | -1.597422E+02 | -7.830566E+00 | 2.777832E+01 |
| 8.618200E+09 | -5.390625E+00 | -1.682422E+02 | -7.715332E+00 | 1.730664E+01 |
| 8.667550E+09 | -5.715820E+00 | -1.766016E+02 | -7.601318E+00 | 7.000977E+00 |
| 8.716900E+09 | -6.180664E+00 | 1.746641E+02 | -7.401367E+00 | -4.358887E+00 |
| 8.766250E+09 | -6.715088E+00 | 1.654453E+02 | -7.202637E+00 | -1.530566E+01 |
| 8.815600E+09 | -7.428711E+00 | 1.561250E+02 | -6.975098E+00 | -2.719824E+01 |
| 8.864950E+09 | -8.295410E+00 | 1.455625E+02 | -6.754150E+00 | -3.890625E+01 |
| 8.914300E+09 | -9.299805E+00 | 1.342344E+02 | -6.525146E+00 | -5.154687E+01 |
| 8.963650E+09 | -1.044385E+01 | 1.206953E+02 | -6.315918E+00 | -6.373828E+01 |
| 9.013000E+09 | -1.152734E+01 | 1.052070E+02 | -6.172119E+00 | -7.676952E+01 |
| 9.062350E+09 | -1.245898E+01 | 8.736328E+01 | -6.011475E+00 | -8.967577E+01 |
| 9.111700E+09 | -1.308105E+01 | 6.854687E+01 | -5.913818E+00 | -1.027187E+02 |
| 9.161050E+09 | -1.352002E+01 | 4.911133E+01 | -5.878174E+00 | -1.156836E+02 |
| 9.210400E+09 | -1.370313E+01 | 2.883496E+01 | -5.872314E+00 | -1.289844E+02 |
| 9.259750E+09 | -1.363574E+01 | 8.630859E+00 | -5.884766E+00 | -1.416953E+02 |

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|---|---|---|---|---|
| 9.309100E+09 | -1.339600E+01 | -1.149316E+01 | -5.988525E+00 | -1.545781E+02 |
| 9.358450E+09 | -1.291504E+01 | -3.153027E+01 | -6.101807E+00 | -1.669765E+02 |
| 9.407800E+09 | -1.221631E+01 | -5.080078E+01 | -6.289551E+00 | -1.793281E+02 |
| 9.457150E+09 | -1.127393E+01 | -6.911718E+01 | -6.441406E+00 | 1.687578E+02 |
| 9.506500E+09 | -1.016992E+01 | -8.514843E+01 | -6.655273E+00 | 1.571953E+02 |
| 9.555850E+09 | -9.060547E+00 | -9.934765E+01 | -6.828369E+00 | 1.459531E+02 |
| 9.605200E+09 | -8.038574E+00 | -1.109453E+02 | -7.055664E+00 | 1.350625E+02 |
| 9.654550E+09 | -7.260986E+00 | -1.215078E+02 | -7.220947E+00 | 1.245508E+02 |
| 9.703900E+09 | -6.598389E+00 | -1.309922E+02 | -7.418457E+00 | 1.141836E+02 |
| 9.753250E+09 | -6.137939E+00 | -1.394766E+02 | -7.548584E+00 | 1.042500E+02 |
| 9.802600E+09 | -5.800293E+00 | -1.469531E+02 | -7.690918E+00 | 9.535156E+01 |
| 9.851950E+09 | -5.565430E+00 | -1.533437E+02 | -7.777588E+00 | 8.751171E+01 |
| 9.901300E+09 | -5.398682E+00 | -1.589844E+02 | -7.862549E+00 | 8.050781E+01 |
| 9.950650E+09 | -5.277832E+00 | -1.635469E+02 | -7.877197E+00 | 7.459374E+01 |
| 1.000000E+10 | -5.236816E+00 | -1.674219E+02 | -7.933105E+00 | 6.957421E+01 |

## A.2. 130-mil wide M-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -2.033203E+01 | -1.462578E+02 | -1.356888E-01 | -4.689258E+01 |
| 1.793500E+08 | -1.977148E+01 | -1.533047E+02 | -1.507568E-01 | -5.322851E+01 |
| 2.287000E+08 | -1.921387E+01 | -1.615078E+02 | -1.664200E-01 | -6.061718E+01 |
| 2.780500E+08 | -1.869531E+01 | -1.708437E+02 | -1.845169E-01 | -6.907421E+01 |
| 3.274000E+08 | -1.824219E+01 | 1.786250E+02 | -2.054214E-01 | -7.859765E+01 |
| 3.767500E+08 | -1.786035E+01 | 1.669375E+02 | -2.222290E-01 | -8.918360E+01 |
| 4.261000E+08 | -1.760742E+01 | 1.540937E+02 | -2.378006E-01 | -1.008476E+02 |
| 4.754500E+08 | -1.773926E+01 | 1.412422E+02 | -2.578278E-01 | -1.125547E+02 |
| 5.248000E+08 | -1.826172E+01 | 1.286797E+02 | -2.755127E-01 | -1.242617E+02 |
| 5.741500E+08 | -1.927148E+01 | 1.163359E+02 | -2.930145E-01 | -1.360312E+02 |
| 6.235000E+08 | -2.114453E+01 | 1.058906E+02 | -3.001862E-01 | -1.478594E+02 |
| 6.728500E+08 | -2.303027E+01 | 1.058984E+02 | -3.079529E-01 | -1.597109E+02 |
| 7.222000E+08 | -2.412109E+01 | 1.073711E+02 | -3.211823E-01 | -1.716328E+02 |
| 7.715500E+08 | -2.485840E+01 | 1.094687E+02 | -3.307800E-01 | 1.763906E+02 |
| 8.209000E+08 | -2.534765E+01 | 1.115039E+02 | -3.419342E-01 | 1.643672E+02 |
| 8.702500E+08 | -2.559570E+01 | 1.135781E+02 | -3.553925E-01 | 1.523047E+02 |
| 9.196000E+08 | -2.568164E+01 | 1.157656E+02 | -3.733063E-01 | 1.401875E+02 |
| 9.689500E+08 | -2.557422E+01 | 1.177851E+02 | -3.926086E-01 | 1.280156E+02 |
| 1.018300E+09 | -2.526172E+01 | 1.198945E+02 | -4.135437E-01 | 1.158828E+02 |
| 1.067650E+09 | -2.470410E+01 | 1.217617E+02 | -4.290771E-01 | 1.036211E+02 |
| 1.117000E+09 | -2.374902E+01 | 1.232891E+02 | -4.496002E-01 | 9.139063E+01 |
| 1.166350E+09 | -2.205078E+01 | 1.230781E+02 | -4.762878E-01 | 7.912109E+01 |
| 1.215700E+09 | -2.044824E+01 | 1.123633E+02 | -4.993896E-01 | 6.680078E+01 |
| 1.265050E+09 | -1.971972E+01 | 1.001875E+02 | -5.158997E-01 | 5.442577E+01 |
| 1.314400E+09 | -1.947558E+01 | 8.752344E+01 | -5.341187E-01 | 4.205664E+01 |
| 1.363750E+09 | -1.962402E+01 | 7.503515E+01 | -5.537109E-01 | 2.962109E+01 |
| 1.413100E+09 | -2.018261E+01 | 6.259766E+01 | -5.686646E-01 | 1.712012E+01 |
| 1.462450E+09 | -2.106348E+01 | 5.053320E+01 | -5.845337E-01 | 4.588135E+00 |
| 1.511800E+09 | -2.248145E+01 | 4.000390E+01 | -6.032715E-01 | -8.009277E+00 |

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|---|---|---|---|---|
| 1.561150E+09 | -2.456055E+01 | 3.044434E+01 | -6.134033E-01 | -2.070313E+01 |
| 1.610500E+09 | -2.653906E+01 | 2.690918E+01 | -6.335754E-01 | -3.341406E+01 |
| 1.659850E+09 | -2.813379E+01 | 2.758594E+01 | -6.537476E-01 | -4.625196E+01 |
| 1.709200E+09 | -2.950098E+01 | 2.877930E+01 | -6.717529E-01 | -5.917578E+01 |
| 1.758550E+09 | -3.054688E+01 | 2.999804E+01 | -6.924744E-01 | -7.215234E+01 |
| 1.807900E+09 | -3.146093E+01 | 3.155762E+01 | -7.158813E-01 | -8.516796E+01 |
| 1.857250E+09 | -3.221484E+01 | 3.208789E+01 | -7.445068E-01 | -9.832811E+01 |
| 1.906600E+09 | -3.266406E+01 | 3.221875E+01 | -7.732239E-01 | -1.115391E+02 |
| 1.955950E+09 | -3.284375E+01 | 3.160351E+01 | -8.111572E-01 | -1.247734E+02 |
| 2.005300E+09 | -3.264648E+01 | 2.986621E+01 | -8.483276E-01 | -1.381641E+02 |
| 2.054650E+09 | -3.178613E+01 | 2.618652E+01 | -8.942566E-01 | -1.516094E+02 |
| 2.104000E+09 | -3.008886E+01 | 2.091797E+01 | -9.444580E-01 | -1.651562E+02 |
| 2.153350E+09 | -2.838476E+01 | 9.288574E+00 | -1.001160E+00 | -1.786719E+02 |
| 2.202700E+09 | -2.682324E+01 | -6.987305E+00 | -1.063416E+00 | 1.677266E+02 |
| 2.252050E+09 | -2.532031E+01 | -2.376367E+01 | -1.125427E+00 | 1.541094E+02 |
| 2.301400E+09 | -2.388476E+01 | -4.045312E+01 | -1.188354E+00 | 1.404844E+02 |
| 2.350750E+09 | -2.231152E+01 | -5.759570E+01 | -1.265381E+00 | 1.267617E+02 |
| 2.400100E+09 | -2.064746E+01 | -7.413671E+01 | -1.359924E+00 | 1.130195E+02 |
| 2.449450E+09 | -1.898535E+01 | -9.050390E+01 | -1.453430E+00 | 9.930077E+01 |
| 2.498800E+09 | -1.724707E+01 | -1.062266E+02 | -1.569580E+00 | 8.554688E+01 |
| 2.548150E+09 | -1.556348E+01 | -1.214453E+02 | -1.683838E+00 | 7.188671E+01 |
| 2.597500E+09 | -1.399365E+01 | -1.361641E+02 | -1.842041E+00 | 5.827929E+01 |
| 2.646850E+09 | -1.257471E+01 | -1.503203E+02 | -1.974609E+00 | 4.467969E+01 |
| 2.696200E+09 | -1.120947E+01 | -1.641797E+02 | -2.159912E+00 | 3.141797E+01 |
| 2.745550E+09 | -1.005225E+01 | -1.775859E+02 | -2.348877E+00 | 1.798828E+01 |
| 2.794900E+09 | -8.979492E+00 | 1.689609E+02 | -2.530396E+00 | 5.104492E+00 |
| 2.844250E+09 | -8.073730E+00 | 1.556015E+02 | -2.767090E+00 | -7.818359E+00 |
| 2.893600E+09 | -7.327393E+00 | 1.424922E+02 | -2.982788E+00 | -2.031054E+01 |
| 2.942950E+09 | -6.677979E+00 | 1.297734E+02 | -3.199829E+00 | -3.264453E+01 |
| 2.992300E+09 | -6.146973E+00 | 1.171836E+02 | -3.396484E+00 | -4.467187E+01 |
| 3.041650E+09 | -5.720703E+00 | 1.046875E+02 | -3.579712E+00 | -5.627930E+01 |
| 3.091000E+09 | -5.408203E+00 | 9.247656E+01 | -3.768555E+00 | -6.764062E+01 |
| 3.140350E+09 | -5.190186E+00 | 8.045313E+01 | -3.866577E+00 | -7.905859E+01 |
| 3.189700E+09 | -5.038818E+00 | 6.865624E+01 | -3.952881E+00 | -8.980860E+01 |
| 3.239050E+09 | -4.969971E+00 | 5.699023E+01 | -4.018555E+00 | -1.008047E+02 |
| 3.288400E+09 | -4.955078E+00 | 4.534961E+01 | -4.005859E+00 | -1.114805E+02 |
| 3.337750E+09 | -5.009766E+00 | 3.371094E+01 | -3.983032E+00 | -1.224414E+02 |
| 3.387100E+09 | -5.140381E+00 | 2.185645E+01 | -3.860718E+00 | -1.331328E+02 |
| 3.436450E+09 | -5.381348E+00 | 9.950684E+00 | -3.763672E+00 | -1.440625E+02 |
| 3.485800E+09 | -5.732178E+00 | -2.113525E+00 | -3.587891E+00 | -1.552344E+02 |
| 3.535150E+09 | -6.178467E+00 | -1.408594E+01 | -3.406738E+00 | -1.664687E+02 |
| 3.584500E+09 | -6.738770E+00 | -2.617773E+01 | -3.215820E+00 | -1.780859E+02 |
| 3.633850E+09 | -7.376953E+00 | -3.849804E+01 | -3.005249E+00 | 1.700312E+02 |
| 3.683200E+09 | -8.153809E+00 | -5.094921E+01 | -2.813477E+00 | 1.582656E+02 |
| 3.732550E+09 | -9.082520E+00 | -6.385937E+01 | -2.653687E+00 | 1.460000E+02 |
| 3.781900E+09 | -1.014453E+01 | -7.691015E+01 | -2.456787E+00 | 1.335938E+02 |
| 3.831250E+09 | -1.142871E+01 | -9.017578E+01 | -2.304321E+00 | 1.211758E+02 |
| 3.880600E+09 | -1.279541E+01 | -1.038008E+02 | -2.170410E+00 | 1.086289E+02 |
| 3.929950E+09 | -1.435693E+01 | -1.174375E+02 | -2.080200E+00 | 9.590624E+01 |

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|---|---|---|---|---|
| 3.979300E+09 | -1.601855E+01 | -1.321719E+02 | -1.969666E+00 | 8.312109E+01 |
| 4.028650E+09 | -1.768066E+01 | -1.471328E+02 | -1.911560E+00 | 7.059375E+01 |
| 4.078000E+09 | -1.937988E+01 | -1.629062E+02 | -1.877686E+00 | 5.789063E+01 |
| 4.127350E+09 | -2.106640E+01 | -1.793047E+02 | -1.838623E+00 | 4.526757E+01 |
| 4.176700E+09 | -2.278027E+01 | 1.636953E+02 | -1.811218E+00 | 3.270117E+01 |
| 4.226050E+09 | -2.442676E+01 | 1.472109E+02 | -1.798157E+00 | 2.012207E+01 |
| 4.275400E+09 | -2.635351E+01 | 1.302422E+02 | -1.789490E+00 | 7.524170E+00 |
| 4.324750E+09 | -2.849512E+01 | 1.123828E+02 | -1.779846E+00 | -5.022217E+00 |
| 4.374100E+09 | -3.013184E+01 | 1.089063E+02 | -1.793762E+00 | -1.758105E+01 |
| 4.423450E+09 | -3.094824E+01 | 1.082461E+02 | -1.806335E+00 | -3.020996E+01 |
| 4.472800E+09 | -3.114746E+01 | 1.070273E+02 | -1.823669E+00 | -4.286523E+01 |
| 4.522150E+09 | -3.077832E+01 | 1.074101E+02 | -1.841431E+00 | -5.556835E+01 |
| 4.571500E+09 | -3.011816E+01 | 1.081055E+02 | -1.866211E+00 | -6.835155E+01 |
| 4.620850E+09 | -2.909180E+01 | 1.091914E+02 | -1.898804E+00 | -8.126171E+01 |
| 4.670200E+09 | -2.778515E+01 | 1.110742E+02 | -1.937866E+00 | -9.426561E+01 |
| 4.719550E+09 | -2.623144E+01 | 1.134961E+02 | -1.998108E+00 | -1.073476E+02 |
| 4.768900E+09 | -2.450098E+01 | 1.153516E+02 | -2.068481E+00 | -1.205195E+02 |
| 4.818250E+09 | -2.225976E+01 | 1.178437E+02 | -2.153076E+00 | -1.338438E+02 |
| 4.867600E+09 | -1.958887E+01 | 1.213750E+02 | -2.247070E+00 | -1.472265E+02 |
| 4.916950E+09 | -1.717969E+01 | 1.108125E+02 | -2.357422E+00 | -1.606953E+02 |
| 4.966300E+09 | -1.547266E+01 | 9.776171E+01 | -2.484253E+00 | -1.742656E+02 |
| 5.015650E+09 | -1.417627E+01 | 8.565233E+01 | -2.605957E+00 | 1.720156E+02 |
| 5.065000E+09 | -1.338477E+01 | 7.333984E+01 | -2.742798E+00 | 1.581953E+02 |
| 5.114350E+09 | -1.289014E+01 | 6.194140E+01 | -2.892822E+00 | 1.441719E+02 |
| 5.163700E+09 | -1.276465E+01 | 5.259766E+01 | -3.050659E+00 | 1.299609E+02 |
| 5.213050E+09 | -1.280371E+01 | 4.541211E+01 | -3.220947E+00 | 1.155156E+02 |
| 5.262400E+09 | -1.275732E+01 | 4.030469E+01 | -3.411987E+00 | 1.007813E+02 |
| 5.311750E+09 | -1.259229E+01 | 3.630078E+01 | -3.640259E+00 | 8.580858E+01 |
| 5.361100E+09 | -1.231104E+01 | 3.284180E+01 | -3.910645E+00 | 7.055469E+01 |
| 5.410450E+09 | -1.193604E+01 | 2.964746E+01 | -4.210205E+00 | 5.523438E+01 |
| 5.459800E+09 | -1.146240E+01 | 2.653125E+01 | -4.572998E+00 | 3.986719E+01 |
| 5.509150E+09 | -1.089746E+01 | 2.353808E+01 | -4.973633E+00 | 2.443750E+01 |
| 5.558500E+09 | -1.022852E+01 | 2.033105E+01 | -5.407227E+00 | 9.136230E+00 |
| 5.607850E+09 | -9.399414E+00 | 1.695996E+01 | -5.878906E+00 | -5.990479E+00 |
| 5.657200E+09 | -8.458496E+00 | 1.288525E+01 | -6.381348E+00 | -2.084863E+01 |
| 5.706550E+09 | -7.361084E+00 | 7.153320E+00 | -6.892090E+00 | -3.544922E+01 |
| 5.755900E+09 | -6.272217E+00 | -5.616760E-01 | -7.391357E+00 | -4.961523E+01 |
| 5.805250E+09 | -5.382568E+00 | -9.979980E+00 | -7.885742E+00 | -6.314843E+01 |
| 5.854600E+09 | -4.696289E+00 | -2.024805E+01 | -8.338867E+00 | -7.647655E+01 |
| 5.903950E+09 | -4.204346E+00 | -3.075488E+01 | -8.703613E+00 | -8.929688E+01 |
| 5.953300E+09 | -3.860352E+00 | -4.147070E+01 | -9.017578E+00 | -1.017305E+02 |
| 6.002650E+09 | -3.629272E+00 | -5.218750E+01 | -9.235840E+00 | -1.141484E+02 |
| 6.052000E+09 | -3.513550E+00 | -6.293554E+01 | -9.361328E+00 | -1.263750E+02 |
| 6.101350E+09 | -3.484863E+00 | -7.371484E+01 | -9.431641E+00 | -1.385625E+02 |
| 6.150700E+09 | -3.536987E+00 | -8.458984E+01 | -9.420410E+00 | -1.507891E+02 |
| 6.200050E+09 | -3.638916E+00 | -9.573828E+01 | -9.342773E+00 | -1.630078E+02 |
| 6.249400E+09 | -3.812134E+00 | -1.070234E+02 | -9.204102E+00 | -1.754766E+02 |
| 6.298750E+09 | -4.049561E+00 | -1.188359E+02 | -9.010254E+00 | 1.720469E+02 |
| 6.348100E+09 | -4.343018E+00 | -1.310547E+02 | -8.782227E+00 | 1.590469E+02 |

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|---|---|---|---|---|
| 6.397450E+09 | -4.707031E+00 | -1.437891E+02 | -8.502930E+00 | 1.460156E+02 |
| 6.446800E+09 | -5.112549E+00 | -1.571484E+02 | -8.235840E+00 | 1.327891E+02 |
| 6.496150E+09 | -5.564209E+00 | -1.710391E+02 | -7.959473E+00 | 1.192773E+02 |
| 6.545500E+09 | -6.045898E+00 | 1.743281E+02 | -7.683105E+00 | 1.057148E+02 |
| 6.594850E+09 | -6.514404E+00 | 1.591328E+02 | -7.417969E+00 | 9.203905E+01 |
| 6.644200E+09 | -6.975098E+00 | 1.432578E+02 | -7.162109E+00 | 7.823828E+01 |
| 6.693550E+09 | -7.393066E+00 | 1.268711E+02 | -6.922363E+00 | 6.441015E+01 |
| 6.742900E+09 | -7.779053E+00 | 1.101367E+02 | -6.694580E+00 | 5.041210E+01 |
| 6.792250E+09 | -8.098633E+00 | 9.319139E+01 | -6.483154E+00 | 3.659765E+01 |
| 6.841600E+09 | -8.365234E+00 | 7.635156E+01 | -6.319580E+00 | 2.260547E+01 |
| 6.890950E+09 | -8.572266E+00 | 5.945313E+01 | -6.131348E+00 | 8.723145E+00 |
| 6.940300E+09 | -8.721680E+00 | 4.302343E+01 | -5.991455E+00 | -4.965820E+00 |
| 6.989650E+09 | -8.866211E+00 | 2.691211E+01 | -5.864258E+00 | -1.876465E+01 |
| 7.039000E+09 | -8.992188E+00 | 1.135840E+01 | -5.737549E+00 | -3.256445E+01 |
| 7.088350E+09 | -9.153320E+00 | -3.326172E+00 | -5.616699E+00 | -4.628515E+01 |
| 7.137700E+09 | -9.405273E+00 | -1.719922E+01 | -5.513672E+00 | -5.989258E+01 |
| 7.187050E+09 | -9.745605E+00 | -2.970996E+01 | -5.423096E+00 | -7.357031E+01 |
| 7.236400E+09 | -1.026465E+01 | -4.046288E+01 | -5.314209E+00 | -8.738672E+01 |
| 7.285750E+09 | -1.085547E+01 | -4.880077E+01 | -5.213379E+00 | -1.010742E+02 |
| 7.335100E+09 | -1.140820E+01 | -5.443749E+01 | -5.150146E+00 | -1.150937E+02 |
| 7.384450E+09 | -1.178857E+01 | -5.844336E+01 | -5.052002E+00 | -1.291641E+02 |
| 7.433800E+09 | -1.199072E+01 | -6.121875E+01 | -5.038818E+00 | -1.431953E+02 |
| 7.483150E+09 | -1.205957E+01 | -6.358984E+01 | -5.044434E+00 | -1.576797E+02 |
| 7.532500E+09 | -1.198096E+01 | -6.538280E+01 | -5.055176E+00 | -1.721562E+02 |
| 7.581850E+09 | -1.181055E+01 | -6.690624E+01 | -5.126709E+00 | 1.736641E+02 |
| 7.631200E+09 | -1.152881E+01 | -6.846874E+01 | -5.250244E+00 | 1.593750E+02 |
| 7.680550E+09 | -1.110303E+01 | -6.993750E+01 | -5.406250E+00 | 1.449375E+02 |
| 7.729900E+09 | -1.059326E+01 | -7.173437E+01 | -5.532715E+00 | 1.306953E+02 |
| 7.779250E+09 | -9.937012E+00 | -7.439843E+01 | -5.756104E+00 | 1.169453E+02 |
| 7.828600E+09 | -9.248535E+00 | -7.834765E+01 | -5.986816E+00 | 1.024766E+02 |
| 7.877950E+09 | -8.667969E+00 | -8.395702E+01 | -6.161621E+00 | 8.884766E+01 |
| 7.927300E+09 | -8.305664E+00 | -8.991014E+01 | -6.409912E+00 | 7.482031E+01 |
| 7.976650E+09 | -8.134277E+00 | -9.561718E+01 | -6.608398E+00 | 6.091015E+01 |
| 8.026000E+09 | -8.055176E+00 | -1.005664E+02 | -6.807129E+00 | 4.701953E+01 |
| 8.075350E+09 | -8.012207E+00 | -1.047812E+02 | -7.037842E+00 | 3.318164E+01 |
| 8.124700E+09 | -7.955078E+00 | -1.084648E+02 | -7.247559E+00 | 1.880371E+01 |
| 8.174050E+09 | -7.849854E+00 | -1.117695E+02 | -7.491699E+00 | 4.611328E+00 |
| 8.223400E+09 | -7.711182E+00 | -1.149453E+02 | -7.705811E+00 | -9.879883E+00 |
| 8.272750E+09 | -7.489746E+00 | -1.181172E+02 | -8.031738E+00 | -2.406836E+01 |
| 8.322100E+09 | -7.200928E+00 | -1.212422E+02 | -8.303711E+00 | -3.894140E+01 |
| 8.371450E+09 | -6.867920E+00 | -1.248242E+02 | -8.647949E+00 | -5.259375E+01 |
| 8.420800E+09 | -6.464844E+00 | -1.288984E+02 | -8.986816E+00 | -6.728125E+01 |
| 8.470150E+09 | -6.017822E+00 | -1.337656E+02 | -9.312500E+00 | -8.067577E+01 |
| 8.519500E+09 | -5.580322E+00 | -1.396484E+02 | -9.656250E+00 | -9.451172E+01 |
| 8.568850E+09 | -5.196777E+00 | -1.465859E+02 | -9.968262E+00 | -1.080156E+02 |
| 8.618200E+09 | -4.923340E+00 | -1.546328E+02 | -1.017383E+01 | -1.212969E+02 |
| 8.667550E+09 | -4.769531E+00 | -1.635000E+02 | -1.041943E+01 | -1.342266E+02 |
| 8.716900E+09 | -4.770264E+00 | -1.729687E+02 | -1.051611E+01 | -1.478672E+02 |
| 8.766250E+09 | -4.922363E+00 | 1.767187E+02 | -1.060693E+01 | -1.609141E+02 |

| | | | | |
|---|---|---|---|---|
| 8.815600E+09 | -5.240967E+00 | 1.658203E+02 | -1.058105E+01 | -1.748594E+02 |
| 8.864950E+09 | -5.741211E+00 | 1.537422E+02 | -1.055029E+01 | 1.713438E+02 |
| 8.914300E+09 | -6.349854E+00 | 1.405703E+02 | -1.043506E+01 | 1.564062E+02 |
| 8.963650E+09 | -7.092529E+00 | 1.256445E+02 | -1.036133E+01 | 1.417578E+02 |
| 9.013000E+09 | -7.827881E+00 | 1.087187E+02 | -1.029736E+01 | 1.257969E+02 |
| 9.062350E+09 | -8.500488E+00 | 9.020311E+01 | -1.020752E+01 | 1.098984E+02 |
| 9.111700E+09 | -9.017090E+00 | 7.034374E+01 | -1.017676E+01 | 9.360546E+01 |
| 9.161050E+09 | -9.382813E+00 | 4.977539E+01 | -1.023633E+01 | 7.707421E+01 |
| 9.210400E+09 | -9.610352E+00 | 2.861523E+01 | -1.029492E+01 | 6.021484E+01 |
| 9.259750E+09 | -9.670898E+00 | 7.392334E+00 | -1.041797E+01 | 4.383789E+01 |
| 9.309100E+09 | -9.590820E+00 | -1.354492E+01 | -1.062891E+01 | 2.718945E+01 |
| 9.358450E+09 | -9.350098E+00 | -3.419726E+01 | -1.084229E+01 | 1.113428E+01 |
| 9.407800E+09 | -8.954590E+00 | -5.392383E+01 | -1.112744E+01 | -4.738037E+00 |
| 9.457150E+09 | -8.419434E+00 | -7.256249E+01 | -1.134961E+01 | -2.009863E+01 |
| 9.506500E+09 | -7.759766E+00 | -8.923828E+01 | -1.161328E+01 | -3.489453E+01 |
| 9.555850E+09 | -7.127441E+00 | -1.039141E+02 | -1.178271E+01 | -4.934960E+01 |
| 9.605200E+09 | -6.546875E+00 | -1.167617E+02 | -1.197852E+01 | -6.326562E+01 |
| 9.654550E+09 | -6.131104E+00 | -1.278945E+02 | -1.205908E+01 | -7.695703E+01 |
| 9.703900E+09 | -5.864746E+00 | -1.378047E+02 | -1.211816E+01 | -9.055079E+01 |
| 9.753250E+09 | -5.729004E+00 | -1.463438E+02 | -1.207227E+01 | -1.039766E+02 |
| 9.802600E+09 | -5.688232E+00 | -1.537188E+02 | -1.202734E+01 | -1.160000E+02 |
| 9.851950E+09 | -5.707764E+00 | -1.599688E+02 | -1.190967E+01 | -1.267578E+02 |
| 9.901300E+09 | -5.779297E+00 | -1.652187E+02 | -1.181982E+01 | -1.363828E+02 |
| 9.950650E+09 | -5.869629E+00 | -1.695547E+02 | -1.165088E+01 | -1.447656E+02 |
| 1.000000E+10 | -5.995117E+00 | -1.730078E+02 | -1.154785E+01 | -1.518828E+02 |

## A.3. 130-mil wide 4-turn structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.930700E+01 | -1.565300E+02 | -1.920000E-01 | -5.726900E+01 |
| 1.793500E+08 | -1.887300E+01 | -1.650100E+02 | -2.090000E-01 | -6.495500E+01 |
| 2.287000E+08 | -1.850800E+01 | -1.749900E+02 | -2.240000E-01 | -7.391900E+01 |
| 2.780500E+08 | -1.826600E+01 | 1.739200E+02 | -2.400000E-01 | -8.417500E+01 |
| 3.274000E+08 | -1.821700E+01 | 1.615000E+02 | -2.590000E-01 | -9.574400E+01 |
| 3.767500E+08 | -1.852400E+01 | 1.479500E+02 | -2.750000E-01 | -1.086200E+02 |
| 4.261000E+08 | -1.936000E+01 | 1.338800E+02 | -2.930000E-01 | -1.228300E+02 |
| 4.754500E+08 | -2.093300E+01 | 1.303700E+02 | -3.090000E-01 | -1.370800E+02 |
| 5.248000E+08 | -2.175200E+01 | 1.297100E+02 | -3.270000E-01 | -1.513800E+02 |
| 5.741500E+08 | -2.223400E+01 | 1.300300E+02 | -3.370000E-01 | -1.657200E+02 |
| 6.235000E+08 | -2.254100E+01 | 1.303000E+02 | -3.580000E-01 | 1.798600E+02 |
| 6.728500E+08 | -2.268400E+01 | 1.306900E+02 | -3.780000E-01 | 1.653900E+02 |
| 7.222000E+08 | -2.269300E+01 | 1.311600E+02 | -3.980000E-01 | 1.509200E+02 |
| 7.715500E+08 | -2.260400E+01 | 1.317400E+02 | -4.250000E-01 | 1.363600E+02 |
| 8.209000E+08 | -2.237700E+01 | 1.320100E+02 | -4.490000E-01 | 1.217300E+02 |
| 8.702500E+08 | -2.198300E+01 | 1.321600E+02 | -4.740000E-01 | 1.070800E+02 |
| 9.196000E+08 | -2.132300E+01 | 1.320700E+02 | -5.020000E-01 | 9.240300E+01 |
| 9.689500E+08 | -2.025800E+01 | 1.309100E+02 | -5.340000E-01 | 7.768800E+01 |
| 1.018300E+09 | -1.886700E+01 | 1.188200E+02 | -5.590000E-01 | 6.289300E+01 |

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|---|---|---|---|---|
| 1.067650E+09 | -1.864200E+01 | 1.039700E+02 | -5.790000E-01 | 4.806800E+01 |
| 1.117000E+09 | -1.940300E+01 | 8.738900E+01 | -6.060000E-01 | 3.316900E+01 |
| 1.166350E+09 | -2.148000E+01 | 6.348300E+01 | -6.210000E-01 | 1.822600E+01 |
| 1.215700E+09 | -2.264100E+01 | 3.289000E+01 | -6.350000E-01 | 3.181900E+00 |
| 1.265050E+09 | -2.344200E+01 | 9.118700E-01 | -6.540000E-01 | -1.196800E+01 |
| 1.314400E+09 | -2.401700E+01 | -3.136200E+01 | -6.710000E-01 | -2.711600E+01 |
| 1.363750E+09 | -2.446600E+01 | -6.398000E+01 | -6.870000E-01 | -4.235500E+01 |
| 1.413100E+09 | -2.483000E+01 | -9.703500E+01 | -7.110000E-01 | -5.765100E+01 |
| 1.462450E+09 | -2.507300E+01 | -1.305100E+02 | -7.300000E-01 | -7.310900E+01 |
| 1.511800E+09 | -2.519500E+01 | -1.641600E+02 | -7.490000E-01 | -8.856500E+01 |
| 1.561150E+09 | -2.517400E+01 | 1.620500E+02 | -7.710000E-01 | -1.039700E+02 |
| 1.610500E+09 | -2.493900E+01 | 1.278100E+02 | -7.970000E-01 | -1.195400E+02 |
| 1.659850E+09 | -2.423100E+01 | 9.386400E+01 | -8.160000E-01 | -1.351400E+02 |
| 1.709200E+09 | -2.260800E+01 | 6.700300E+01 | -8.480000E-01 | -1.508100E+02 |
| 1.758550E+09 | -2.222200E+01 | 4.583100E+01 | -8.700000E-01 | -1.664900E+02 |
| 1.807900E+09 | -2.250600E+01 | 2.552400E+01 | -8.860000E-01 | 1.777600E+02 |
| 1.857250E+09 | -2.325900E+01 | 5.457500E+00 | -9.090000E-01 | 1.618700E+02 |
| 1.906600E+09 | -2.443800E+01 | -1.378000E+01 | -9.350000E-01 | 1.459600E+02 |
| 1.955950E+09 | -2.583600E+01 | -3.135600E+01 | -9.550000E-01 | 1.299400E+02 |
| 2.005300E+09 | -2.719800E+01 | -4.735100E+01 | -9.800000E-01 | 1.139100E+02 |
| 2.054650E+09 | -2.842700E+01 | -6.042600E+01 | -1.005000E+00 | 9.771100E+01 |
| 2.104000E+09 | -2.935500E+01 | -7.219100E+01 | -1.040000E+00 | 8.135800E+01 |
| 2.153350E+09 | -3.007100E+01 | -8.206400E+01 | -1.077000E+00 | 6.496400E+01 |
| 2.202700E+09 | -3.040300E+01 | -9.091300E+01 | -1.125000E+00 | 4.846200E+01 |
| 2.252050E+09 | -3.041100E+01 | -9.792000E+01 | -1.168000E+00 | 3.185900E+01 |
| 2.301400E+09 | -2.995600E+01 | -1.032900E+02 | -1.237000E+00 | 1.515700E+01 |
| 2.350750E+09 | -2.904800E+01 | -1.073700E+02 | -1.317000E+00 | -1.716600E+00 |
| 2.400100E+09 | -2.764100E+01 | -1.112100E+02 | -1.406000E+00 | -1.860000E+01 |
| 2.449450E+09 | -2.574900E+01 | -1.153000E+02 | -1.533000E+00 | -3.571100E+01 |
| 2.498800E+09 | -2.350000E+01 | -1.203500E+02 | -1.635000E+00 | -5.264100E+01 |
| 2.548150E+09 | -2.116600E+01 | -1.265500E+02 | -1.815000E+00 | -6.975500E+01 |
| 2.597500E+09 | -1.882100E+01 | -1.352000E+02 | -2.002000E+00 | -8.676900E+01 |
| 2.646850E+09 | -1.659700E+01 | -1.447700E+02 | -2.194000E+00 | -1.039000E+02 |
| 2.696200E+09 | -1.443800E+01 | -1.555400E+02 | -2.492000E+00 | -1.208200E+02 |
| 2.745550E+09 | -1.248800E+01 | -1.667600E+02 | -2.646000E+00 | -1.376800E+02 |
| 2.794900E+09 | -1.065700E+01 | -1.793700E+02 | -3.082000E+00 | -1.546500E+02 |
| 2.844250E+09 | -9.073000E+00 | 1.673800E+02 | -3.440000E+00 | -1.701100E+02 |
| 2.893600E+09 | -7.721000E+00 | 1.534500E+02 | -3.715000E+00 | 1.738900E+02 |
| 2.942950E+09 | -6.633000E+00 | 1.395500E+02 | -4.203000E+00 | 1.583900E+02 |
| 2.992300E+09 | -5.745000E+00 | 1.256700E+02 | -4.473000E+00 | 1.441700E+02 |
| 3.041650E+09 | -5.051000E+00 | 1.118400E+02 | -4.835000E+00 | 1.298400E+02 |
| 3.091000E+09 | -4.517000E+00 | 9.821800E+01 | -5.038000E+00 | 1.162500E+02 |
| 3.140350E+09 | -4.142000E+00 | 8.469500E+01 | -5.312000E+00 | 1.028400E+02 |
| 3.189700E+09 | -3.903000E+00 | 7.136700E+01 | -5.454000E+00 | 9.026200E+01 |
| 3.239050E+09 | -3.782000E+00 | 5.808200E+01 | -5.430000E+00 | 7.718700E+01 |
| 3.288400E+09 | -3.788000E+00 | 4.483000E+01 | -5.562000E+00 | 6.506200E+01 |
| 3.337750E+09 | -3.906000E+00 | 3.149200E+01 | -5.330000E+00 | 5.280600E+01 |
| 3.387100E+09 | -4.171000E+00 | 1.800500E+01 | -5.187000E+00 | 3.978800E+01 |
| 3.436450E+09 | -4.566000E+00 | 4.301100E+00 | -4.936000E+00 | 2.737900E+01 |

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|---|---|---|---|---|
| 3.485800E+09 | -5.142000E+00 | -9.846500E+00 | -4.546000E+00 | 1.401600E+01 |
| 3.535150E+09 | -5.927000E+00 | -2.423900E+01 | -4.289000E+00 | 4.696700E-01 |
| 3.584500E+09 | -6.983000E+00 | -3.910200E+01 | -3.869000E+00 | -1.347200E+01 |
| 3.633850E+09 | -8.406000E+00 | -5.382600E+01 | -3.583000E+00 | -2.810400E+01 |
| 3.683200E+09 | -1.028100E+01 | -6.772400E+01 | -3.201000E+00 | -4.273100E+01 |
| 3.732550E+09 | -1.263300E+01 | -7.820800E+01 | -2.930000E+00 | -5.798700E+01 |
| 3.781900E+09 | -1.491300E+01 | -8.419800E+01 | -2.712000E+00 | -7.276100E+01 |
| 3.831250E+09 | -1.681600E+01 | -8.850400E+01 | -2.465000E+00 | -8.845900E+01 |
| 3.880600E+09 | -1.849600E+01 | -9.271000E+01 | -2.303000E+00 | -1.037500E+02 |
| 3.929950E+09 | -2.000300E+01 | -9.689000E+01 | -2.112000E+00 | -1.195900E+02 |
| 3.979300E+09 | -2.136300E+01 | -1.014500E+02 | -2.101000E+00 | -1.352600E+02 |
| 4.028650E+09 | -2.258700E+01 | -1.061700E+02 | -2.001000E+00 | -1.503100E+02 |
| 4.078000E+09 | -2.358300E+01 | -1.113300E+02 | -1.945000E+00 | -1.662100E+02 |
| 4.127350E+09 | -2.435500E+01 | -1.164500E+02 | -1.997000E+00 | 1.783900E+02 |
| 4.176700E+09 | -2.474600E+01 | -1.217000E+02 | -1.987000E+00 | 1.632500E+02 |
| 4.226050E+09 | -2.462800E+01 | -1.276400E+02 | -2.000000E+00 | 1.479100E+02 |
| 4.275400E+09 | -2.393300E+01 | -1.366000E+02 | -2.022000E+00 | 1.327200E+02 |
| 4.324750E+09 | -2.313400E+01 | -1.495400E+02 | -2.039000E+00 | 1.174100E+02 |
| 4.374100E+09 | -2.251300E+01 | -1.636900E+02 | -2.082000E+00 | 1.021000E+02 |
| 4.423450E+09 | -2.191500E+01 | -1.777800E+02 | -2.125000E+00 | 8.687600E+01 |
| 4.472800E+09 | -2.128700E+01 | 1.684500E+02 | -2.154000E+00 | 7.155300E+01 |
| 4.522150E+09 | -2.059800E+01 | 1.552500E+02 | -2.198000E+00 | 5.610600E+01 |
| 4.571500E+09 | -1.984100E+01 | 1.425300E+02 | -2.251000E+00 | 4.067800E+01 |
| 4.620850E+09 | -1.909200E+01 | 1.303700E+02 | -2.300000E+00 | 2.525600E+01 |
| 4.670200E+09 | -1.833900E+01 | 1.186500E+02 | -2.335000E+00 | 9.674800E+00 |
| 4.719550E+09 | -1.770100E+01 | 1.071400E+02 | -2.379000E+00 | -6.016400E+00 |
| 4.768900E+09 | -1.728500E+01 | 9.614400E+01 | -2.412000E+00 | -2.179600E+01 |
| 4.818250E+09 | -1.718800E+01 | 8.676700E+01 | -2.456000E+00 | -3.788800E+01 |
| 4.867600E+09 | -1.719100E+01 | 8.071800E+01 | -2.516000E+00 | -5.401300E+01 |
| 4.916950E+09 | -1.700300E+01 | 7.669400E+01 | -2.561000E+00 | -7.039100E+01 |
| 4.966300E+09 | -1.662400E+01 | 7.339800E+01 | -2.638000E+00 | -8.710400E+01 |
| 5.015650E+09 | -1.613400E+01 | 7.011100E+01 | -2.760000E+00 | -1.039900E+02 |
| 5.065000E+09 | -1.559000E+01 | 6.688500E+01 | -2.904000E+00 | -1.209300E+02 |
| 5.114350E+09 | -1.499900E+01 | 6.370600E+01 | -3.073000E+00 | -1.381000E+02 |
| 5.163700E+09 | -1.437500E+01 | 6.060100E+01 | -3.279000E+00 | -1.554900E+02 |
| 5.213050E+09 | -1.371300E+01 | 5.752300E+01 | -3.529000E+00 | -1.729800E+02 |
| 5.262400E+09 | -1.297900E+01 | 5.444700E+01 | -3.800000E+00 | 1.694700E+02 |
| 5.311750E+09 | -1.213800E+01 | 5.133400E+01 | -4.078000E+00 | 1.516400E+02 |
| 5.361100E+09 | -1.112500E+01 | 4.739600E+01 | -4.395000E+00 | 1.334700E+02 |
| 5.410450E+09 | -1.012600E+01 | 4.134700E+01 | -4.760000E+00 | 1.149300E+02 |
| 5.459800E+09 | -9.321000E+00 | 3.418900E+01 | -5.214000E+00 | 9.604200E+01 |
| 5.509150E+09 | -8.693000E+00 | 2.693700E+01 | -5.741000E+00 | 7.699100E+01 |
| 5.558500E+09 | -8.166000E+00 | 1.985500E+01 | -6.318000E+00 | 5.807000E+01 |
| 5.607850E+09 | -7.708000E+00 | 1.289000E+01 | -6.971000E+00 | 3.856900E+01 |
| 5.657200E+09 | -7.292000E+00 | 6.119400E+00 | -7.793000E+00 | 1.956400E+01 |
| 5.706550E+09 | -6.890000E+00 | -4.765300E-01 | -8.574000E+00 | 1.051900E+00 |
| 5.755900E+09 | -6.468000E+00 | -6.984600E+00 | -9.364000E+00 | -1.778800E+01 |
| 5.805250E+09 | -6.001000E+00 | -1.359000E+01 | -1.028600E+01 | -3.582500E+01 |
| 5.854600E+09 | -5.463000E+00 | -2.063200E+01 | -1.112900E+01 | -5.315300E+01 |

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|---|---|---|---|---|
| 5.903950E+09 | -4.858000E+00 | -2.871100E+01 | -1.196500E+01 | -6.997100E+01 |
| 5.953300E+09 | -4.291000E+00 | -3.828500E+01 | -1.277700E+01 | -8.627300E+01 |
| 6.002650E+09 | -3.877000E+00 | -4.898300E+01 | -1.336400E+01 | -1.012000E+02 |
| 6.052000E+09 | -3.629000E+00 | -6.025000E+01 | -1.379200E+01 | -1.160300E+02 |
| 6.101350E+09 | -3.517000E+00 | -7.185600E+01 | -1.410100E+01 | -1.311100E+02 |
| 6.150700E+09 | -3.513000E+00 | -8.367900E+01 | -1.426600E+01 | -1.447200E+02 |
| 6.200050E+09 | -3.591000E+00 | -9.579100E+01 | -1.416100E+01 | -1.595900E+02 |
| 6.249400E+09 | -3.742000E+00 | -1.082900E+02 | -1.398600E+01 | -1.739100E+02 |
| 6.298750E+09 | -3.956000E+00 | -1.212600E+02 | -1.363900E+01 | 1.716700E+02 |
| 6.348100E+09 | -4.227000E+00 | -1.347900E+02 | -1.318000E+01 | 1.562500E+02 |
| 6.397450E+09 | -4.548000E+00 | -1.489500E+02 | -1.268900E+01 | 1.412600E+02 |
| 6.446800E+09 | -4.906000E+00 | -1.637900E+02 | -1.210500E+01 | 1.252100E+02 |
| 6.496150E+09 | -5.297000E+00 | -1.793500E+02 | -1.143400E+01 | 1.095100E+02 |
| 6.545500E+09 | -5.707000E+00 | 1.643800E+02 | -1.087400E+01 | 9.252400E+01 |
| 6.594850E+09 | -6.127000E+00 | 1.475300E+02 | -1.032800E+01 | 7.589600E+01 |
| 6.644200E+09 | -6.547000E+00 | 1.302200E+02 | -9.723000E+00 | 5.956500E+01 |
| 6.693550E+09 | -6.972000E+00 | 1.126000E+02 | -9.212000E+00 | 4.224200E+01 |
| 6.742900E+09 | -7.393000E+00 | 9.483100E+01 | -8.710000E+00 | 2.555700E+01 |
| 6.792250E+09 | -7.825000E+00 | 7.710600E+01 | -8.269000E+00 | 8.547400E+00 |
| 6.841600E+09 | -8.280000E+00 | 5.955700E+01 | -7.836000E+00 | -8.507500E+00 |
| 6.890950E+09 | -8.795000E+00 | 4.258700E+01 | -7.442000E+00 | -2.531900E+01 |
| 6.940300E+09 | -9.394000E+00 | 2.655300E+01 | -7.091000E+00 | -4.268700E+01 |
| 6.989650E+09 | -1.012300E+01 | 1.225300E+01 | -6.744000E+00 | -5.947000E+01 |
| 7.039000E+09 | -1.088500E+01 | 6.028700E-01 | -6.519000E+00 | -7.672900E+01 |
| 7.088350E+09 | -1.151900E+01 | -8.221900E+00 | -6.215000E+00 | -9.348300E+01 |
| 7.137700E+09 | -1.192700E+01 | -1.518600E+01 | -5.988000E+00 | -1.108000E+02 |
| 7.187050E+09 | -1.213200E+01 | -2.103700E+01 | -5.937000E+00 | -1.280000E+02 |
| 7.236400E+09 | -1.216500E+01 | -2.622700E+01 | -5.703000E+00 | -1.450600E+02 |
| 7.285750E+09 | -1.209100E+01 | -3.092700E+01 | -5.648000E+00 | -1.624700E+02 |
| 7.335100E+09 | -1.191600E+01 | -3.532700E+01 | -5.655000E+00 | -1.793500E+02 |
| 7.384450E+09 | -1.166400E+01 | -3.950100E+01 | -5.670000E+00 | 1.640400E+02 |
| 7.433800E+09 | -1.133000E+01 | -4.373900E+01 | -5.631000E+00 | 1.471000E+02 |
| 7.483150E+09 | -1.093000E+01 | -4.817200E+01 | -5.782000E+00 | 1.302000E+02 |
| 7.532500E+09 | -1.048600E+01 | -5.342900E+01 | -5.876000E+00 | 1.144100E+02 |
| 7.581850E+09 | -1.016100E+01 | -5.975600E+01 | -5.763000E+00 | 9.800200E+01 |
| 7.631200E+09 | -1.010700E+01 | -6.603300E+01 | -5.884000E+00 | 8.090700E+01 |
| 7.680550E+09 | -1.016300E+01 | -7.072900E+01 | -6.009000E+00 | 6.459800E+01 |
| 7.729900E+09 | -1.015000E+01 | -7.439700E+01 | -5.950000E+00 | 4.762700E+01 |
| 7.779250E+09 | -1.007800E+01 | -7.773800E+01 | -6.211000E+00 | 3.058600E+01 |
| 7.828600E+09 | -9.953000E+00 | -8.092900E+01 | -6.257000E+00 | 1.445900E+01 |
| 7.877950E+09 | -9.801000E+00 | -8.407200E+01 | -6.325000E+00 | -3.773800E+00 |
| 7.927300E+09 | -9.622000E+00 | -8.705800E+01 | -6.734000E+00 | -2.096900E+01 |
| 7.976650E+09 | -9.407000E+00 | -8.992700E+01 | -6.886000E+00 | -3.722000E+01 |
| 8.026000E+09 | -9.142000E+00 | -9.272200E+01 | -6.958000E+00 | -5.540500E+01 |
| 8.075350E+09 | -8.797000E+00 | -9.548600E+01 | -7.366000E+00 | -7.331600E+01 |
| 8.124700E+09 | -8.337000E+00 | -9.856100E+01 | -7.815000E+00 | -8.939600E+01 |
| 8.174050E+09 | -7.779000E+00 | -1.029000E+02 | -7.899000E+00 | -1.066900E+02 |
| 8.223400E+09 | -7.330000E+00 | -1.086600E+02 | -8.201000E+00 | -1.252500E+02 |
| 8.272750E+09 | -7.061000E+00 | -1.147900E+02 | -8.792000E+00 | -1.425400E+02 |

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|---|---|---|---|---|
| 8.322100E+09 | -6.893000E+00 | -1.206700E+02 | -9.009000E+00 | -1.589000E+02 |
| 8.371450E+09 | -6.772000E+00 | -1.264000E+02 | -9.397000E+00 | -1.777900E+02 |
| 8.420800E+09 | -6.676000E+00 | -1.319700E+02 | -9.930000E+00 | 1.648300E+02 |
| 8.470150E+09 | -6.586000E+00 | -1.375200E+02 | -1.026200E+01 | 1.473700E+02 |
| 8.519500E+09 | -6.501000E+00 | -1.431600E+02 | -1.086200E+01 | 1.294400E+02 |
| 8.568850E+09 | -6.407000E+00 | -1.489900E+02 | -1.140200E+01 | 1.141300E+02 |
| 8.618200E+09 | -6.285000E+00 | -1.552300E+02 | -1.169600E+01 | 9.585700E+01 |
| 8.667550E+09 | -6.118000E+00 | -1.621700E+02 | -1.230800E+01 | 7.738200E+01 |
| 8.716900E+09 | -5.927000E+00 | -1.702800E+02 | -1.301200E+01 | 6.183900E+01 |
| 8.766250E+09 | -5.787000E+00 | 1.798200E+02 | -1.336600E+01 | 4.555500E+01 |
| 8.815600E+09 | -5.806000E+00 | 1.681300E+02 | -1.375700E+01 | 2.903100E+01 |
| 8.864950E+09 | -6.027000E+00 | 1.548400E+02 | -1.419000E+01 | 1.159900E+01 |
| 8.914300E+09 | -6.417000E+00 | 1.400500E+02 | -1.458400E+01 | -4.474200E+00 |
| 8.963650E+09 | -6.912000E+00 | 1.236400E+02 | -1.480200E+01 | -2.108600E+01 |
| 9.013000E+09 | -7.432000E+00 | 1.056300E+02 | -1.494400E+01 | -3.915100E+01 |
| 9.062350E+09 | -7.896000E+00 | 8.626200E+01 | -1.518000E+01 | -5.806800E+01 |
| 9.111700E+09 | -8.266000E+00 | 6.591400E+01 | -1.546500E+01 | -7.731200E+01 |
| 9.161050E+09 | -8.527000E+00 | 4.500000E+01 | -1.567800E+01 | -9.556000E+01 |
| 9.210400E+09 | -8.677000E+00 | 2.380100E+01 | -1.584900E+01 | -1.155000E+02 |
| 9.259750E+09 | -8.711000E+00 | 2.590000E+00 | -1.613100E+01 | -1.363200E+02 |
| 9.309100E+09 | -8.636000E+00 | -1.828300E+01 | -1.651400E+01 | -1.557100E+02 |
| 9.358450E+09 | -8.445000E+00 | -3.854400E+01 | -1.667800E+01 | -1.747200E+02 |
| 9.407800E+09 | -8.139000E+00 | -5.780300E+01 | -1.677000E+01 | 1.653600E+02 |
| 9.457150E+09 | -7.750000E+00 | -7.572900E+01 | -1.706500E+01 | 1.458000E+02 |
| 9.506500E+09 | -7.325000E+00 | -9.192000E+01 | -1.717800E+01 | 1.275700E+02 |
| 9.555850E+09 | -6.937000E+00 | -1.062700E+02 | -1.712600E+01 | 1.097200E+02 |
| 9.605200E+09 | -6.656000E+00 | -1.186700E+02 | -1.696600E+01 | 9.182800E+01 |
| 9.654550E+09 | -6.506000E+00 | -1.293300E+02 | -1.677300E+01 | 7.335300E+01 |
| 9.703900E+09 | -6.464000E+00 | -1.382900E+02 | -1.656200E+01 | 5.597500E+01 |
| 9.753250E+09 | -6.485000E+00 | -1.458700E+02 | -1.604000E+01 | 3.873900E+01 |
| 9.802600E+09 | -6.567000E+00 | -1.521100E+02 | -1.554700E+01 | 2.279300E+01 |
| 9.851950E+09 | -6.689000E+00 | -1.572300E+02 | -1.503600E+01 | 8.543200E+00 |
| 9.901300E+09 | -6.838000E+00 | -1.612900E+02 | -1.452400E+01 | -5.129200E+00 |
| 9.950650E+09 | -6.997000E+00 | -1.644200E+02 | -1.421400E+01 | -1.626900E+01 |
| 1.000000E+10 | -7.153000E+00 | -1.666800E+02 | -1.365900E+01 | -2.550200E+01 |

## A.4. 130-mil wide 5-turn structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.779600E+01 | -1.661200E+02 | -1.340000E-01 | -6.662200E+01 |
| 1.793500E+08 | -1.777400E+01 | -1.756100E+02 | -1.480000E-01 | -7.559700E+01 |
| 2.287000E+08 | -1.800600E+01 | 1.730600E+02 | -1.570000E-01 | -8.608200E+01 |
| 2.780500E+08 | -1.868800E+01 | 1.604200E+02 | -1.720000E-01 | -9.810100E+01 |
| 3.274000E+08 | -2.086600E+01 | 1.477800E+02 | -1.850000E-01 | -1.116600E+02 |
| 3.767500E+08 | -2.177000E+01 | 1.474700E+02 | -2.020000E-01 | -1.267600E+02 |
| 4.261000E+08 | -2.214600E+01 | 1.456400E+02 | -2.210000E-01 | -1.434000E+02 |
| 4.754500E+08 | -2.238100E+01 | 1.435300E+02 | -2.450000E-01 | -1.601000E+02 |
| 5.248000E+08 | -2.254300E+01 | 1.412100E+02 | -2.720000E-01 | -1.768400E+02 |

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|---|---|---|---|---|
| 5.741500E+08 | -2.263400E+01 | 1.390900E+02 | -2.880000E-01 | 1.664200E+02 |
| 6.235000E+08 | -2.267900E+01 | 1.367200E+02 | -3.160000E-01 | 1.495700E+02 |
| 6.728500E+08 | -2.267100E+01 | 1.342700E+02 | -3.440000E-01 | 1.327100E+02 |
| 7.222000E+08 | -2.255300E+01 | 1.317900E+02 | -3.660000E-01 | 1.158000E+02 |
| 7.715500E+08 | -2.235700E+01 | 1.296000E+02 | -3.960000E-01 | 9.884400E+01 |
| 8.209000E+08 | -2.195100E+01 | 1.271100E+02 | -4.190000E-01 | 8.181700E+01 |
| 8.702500E+08 | -2.055600E+01 | 1.233300E+02 | -4.450000E-01 | 6.474800E+01 |
| 9.196000E+08 | -2.126300E+01 | 1.103800E+02 | -4.680000E-01 | 4.761900E+01 |
| 9.689500E+08 | -2.181900E+01 | 1.059700E+02 | -4.930000E-01 | 3.041300E+01 |
| 1.018300E+09 | -2.213400E+01 | 1.023600E+02 | -5.090000E-01 | 1.316400E+01 |
| 1.067650E+09 | -2.237300E+01 | 9.917100E+01 | -5.210000E-01 | -4.163800E+00 |
| 1.117000E+09 | -2.254500E+01 | 9.580100E+01 | -5.540000E-01 | -2.167600E+01 |
| 1.166350E+09 | -2.269600E+01 | 9.273100E+01 | -5.660000E-01 | -3.913700E+01 |
| 1.215700E+09 | -2.278800E+01 | 8.984100E+01 | -5.820000E-01 | -5.679700E+01 |
| 1.265050E+09 | -2.292600E+01 | 8.683900E+01 | -6.160000E-01 | -7.452700E+01 |
| 1.314400E+09 | -2.298900E+01 | 8.415800E+01 | -6.310000E-01 | -9.227800E+01 |
| 1.363750E+09 | -2.299300E+01 | 8.151400E+01 | -6.560000E-01 | -1.101400E+02 |
| 1.413100E+09 | -2.283400E+01 | 7.936900E+01 | -6.830000E-01 | -1.280600E+02 |
| 1.462450E+09 | -2.230800E+01 | 7.362400E+01 | -7.110000E-01 | -1.460900E+02 |
| 1.511800E+09 | -2.297200E+01 | 6.462200E+01 | -7.360000E-01 | -1.641700E+02 |
| 1.561150E+09 | -2.384200E+01 | 5.909000E+01 | -7.640000E-01 | 1.776800E+02 |
| 1.610500E+09 | -2.455200E+01 | 5.533300E+01 | -7.890000E-01 | 1.594400E+02 |
| 1.659850E+09 | -2.534600E+01 | 5.204600E+01 | -8.040000E-01 | 1.411600E+02 |
| 1.709200E+09 | -2.615300E+01 | 4.903200E+01 | -8.320000E-01 | 1.226900E+02 |
| 1.758550E+09 | -2.698000E+01 | 4.562800E+01 | -8.560000E-01 | 1.042700E+02 |
| 1.807900E+09 | -2.773900E+01 | 4.305800E+01 | -8.670000E-01 | 8.575200E+01 |
| 1.857250E+09 | -2.841600E+01 | 3.938300E+01 | -9.000000E-01 | 6.705000E+01 |
| 1.906600E+09 | -2.898700E+01 | 3.549500E+01 | -9.300000E-01 | 4.836600E+01 |
| 1.955950E+09 | -2.902900E+01 | 2.991000E+01 | -9.600000E-01 | 2.954100E+01 |
| 2.005300E+09 | -2.852500E+01 | 2.251500E+01 | -9.850000E-01 | 1.072300E+01 |
| 2.054650E+09 | -2.733000E+01 | 9.516900E+00 | -1.011000E+00 | -8.239700E+00 |
| 2.104000E+09 | -2.634200E+01 | -8.210900E+00 | -1.057000E+00 | -2.729700E+01 |
| 2.153350E+09 | -2.560500E+01 | -2.791800E+01 | -1.082000E+00 | -4.641700E+01 |
| 2.202700E+09 | -2.490600E+01 | -4.827400E+01 | -1.135000E+00 | -6.575000E+01 |
| 2.252050E+09 | -2.427700E+01 | -6.870900E+01 | -1.179000E+00 | -8.514300E+01 |
| 2.301400E+09 | -2.377500E+01 | -8.811600E+01 | -1.235000E+00 | -1.047000E+02 |
| 2.350750E+09 | -2.343300E+01 | -1.053900E+02 | -1.312000E+00 | -1.244300E+02 |
| 2.400100E+09 | -2.285500E+01 | -1.183000E+02 | -1.398000E+00 | -1.442600E+02 |
| 2.449450E+09 | -2.178300E+01 | -1.290100E+02 | -1.520000E+00 | -1.644000E+02 |
| 2.498800E+09 | -2.056700E+01 | -1.381800E+02 | -1.642000E+00 | 1.756100E+02 |
| 2.548150E+09 | -1.918200E+01 | -1.463200E+02 | -1.836000E+00 | 1.552700E+02 |
| 2.597500E+09 | -1.775800E+01 | -1.541700E+02 | -2.067000E+00 | 1.349500E+02 |
| 2.646850E+09 | -1.633200E+01 | -1.613800E+02 | -2.303000E+00 | 1.145300E+02 |
| 2.696200E+09 | -1.494300E+01 | -1.685900E+02 | -2.704000E+00 | 9.408600E+01 |
| 2.745550E+09 | -1.352700E+01 | -1.754700E+02 | -2.950000E+00 | 7.429100E+01 |
| 2.794900E+09 | -1.203000E+01 | 1.775500E+02 | -3.496000E+00 | 5.392800E+01 |
| 2.844250E+09 | -1.037400E+01 | 1.700600E+02 | -4.024000E+00 | 3.547800E+01 |
| 2.893600E+09 | -8.509000E+00 | 1.600800E+02 | -4.423000E+00 | 1.669100E+01 |
| 2.942950E+09 | -6.846000E+00 | 1.468000E+02 | -5.053000E+00 | -1.711100E+00 |

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|---|---|---|---|---|
| 2.992300E+09 | -5.598000E+00 | 1.318700E+02 | -5.476000E+00 | -1.836500E+01 |
| 3.041650E+09 | -4.673000E+00 | 1.166700E+02 | -5.952000E+00 | -3.505600E+01 |
| 3.091000E+09 | -4.009000E+00 | 1.014700E+02 | -6.267000E+00 | -5.069600E+01 |
| 3.140350E+09 | -3.573000E+00 | 8.649500E+01 | -6.616000E+00 | -6.608700E+01 |
| 3.189700E+09 | -3.310000E+00 | 7.181800E+01 | -6.797000E+00 | -8.047900E+01 |
| 3.239050E+09 | -3.194000E+00 | 5.733900E+01 | -6.749000E+00 | -9.519700E+01 |
| 3.288400E+09 | -3.217000E+00 | 4.296900E+01 | -6.833000E+00 | -1.094000E+02 |
| 3.337750E+09 | -3.373000E+00 | 2.857100E+01 | -6.526000E+00 | -1.233400E+02 |
| 3.387100E+09 | -3.687000E+00 | 1.404200E+01 | -6.230000E+00 | -1.384700E+02 |
| 3.436450E+09 | -4.190000E+00 | -7.333400E-01 | -5.874000E+00 | -1.533500E+02 |
| 3.485800E+09 | -4.946000E+00 | -1.576000E+01 | -5.351000E+00 | -1.687600E+02 |
| 3.535150E+09 | -6.024000E+00 | -3.077400E+01 | -4.931000E+00 | 1.749300E+02 |
| 3.584500E+09 | -7.515000E+00 | -4.531000E+01 | -4.405000E+00 | 1.582300E+02 |
| 3.633850E+09 | -9.586000E+00 | -5.813600E+01 | -3.994000E+00 | 1.408100E+02 |
| 3.683200E+09 | -1.179600E+01 | -6.512300E+01 | -3.504000E+00 | 1.233100E+02 |
| 3.732550E+09 | -1.368400E+01 | -6.992700E+01 | -3.149000E+00 | 1.050700E+02 |
| 3.781900E+09 | -1.533800E+01 | -7.382100E+01 | -2.879000E+00 | 8.738800E+01 |
| 3.831250E+09 | -1.684300E+01 | -7.745800E+01 | -2.590000E+00 | 6.874000E+01 |
| 3.880600E+09 | -1.822900E+01 | -8.128400E+01 | -2.411000E+00 | 5.061400E+01 |
| 3.929950E+09 | -1.952900E+01 | -8.525700E+01 | -2.219000E+00 | 3.203200E+01 |
| 3.979300E+09 | -2.066900E+01 | -8.947500E+01 | -2.205000E+00 | 1.382500E+01 |
| 4.028650E+09 | -2.159200E+01 | -9.419000E+01 | -2.099000E+00 | -3.926200E+00 |
| 4.078000E+09 | -2.218900E+01 | -9.971900E+01 | -2.076000E+00 | -2.220600E+01 |
| 4.127350E+09 | -2.234900E+01 | -1.065300E+02 | -2.100000E+00 | -3.985700E+01 |
| 4.176700E+09 | -2.189400E+01 | -1.154500E+02 | -2.094000E+00 | -5.752400E+01 |
| 4.226050E+09 | -2.123500E+01 | -1.306700E+02 | -2.124000E+00 | -7.515900E+01 |
| 4.275400E+09 | -2.090000E+01 | -1.484500E+02 | -2.141000E+00 | -9.264100E+01 |
| 4.324750E+09 | -2.077600E+01 | -1.668400E+02 | -2.161000E+00 | -1.103400E+02 |
| 4.374100E+09 | -2.077200E+01 | 1.746200E+02 | -2.211000E+00 | -1.279600E+02 |
| 4.423450E+09 | -2.105400E+01 | 1.573300E+02 | -2.255000E+00 | -1.455900E+02 |
| 4.472800E+09 | -2.136000E+01 | 1.425700E+02 | -2.302000E+00 | -1.633100E+02 |
| 4.522150E+09 | -2.165200E+01 | 1.311200E+02 | -2.343000E+00 | 1.788100E+02 |
| 4.571500E+09 | -2.162200E+01 | 1.227700E+02 | -2.417000E+00 | 1.608000E+02 |
| 4.620850E+09 | -2.128200E+01 | 1.161400E+02 | -2.485000E+00 | 1.428500E+02 |
| 4.670200E+09 | -2.075200E+01 | 1.105400E+02 | -2.560000E+00 | 1.245500E+02 |
| 4.719550E+09 | -2.009200E+01 | 1.054300E+02 | -2.660000E+00 | 1.063400E+02 |
| 4.768900E+09 | -1.937200E+01 | 1.007700E+02 | -2.732000E+00 | 8.795900E+01 |
| 4.818250E+09 | -1.855900E+01 | 9.644200E+01 | -2.845000E+00 | 6.926600E+01 |
| 4.867600E+09 | -1.773000E+01 | 9.171500E+01 | -2.961000E+00 | 5.071600E+01 |
| 4.916950E+09 | -1.692900E+01 | 8.714900E+01 | -3.046000E+00 | 3.194300E+01 |
| 4.966300E+09 | -1.600200E+01 | 8.196100E+01 | -3.139000E+00 | 1.288700E+01 |
| 5.015650E+09 | -1.527400E+01 | 7.588400E+01 | -3.248000E+00 | -6.400900E+00 |
| 5.065000E+09 | -1.463700E+01 | 7.024200E+01 | -3.361000E+00 | -2.588200E+01 |
| 5.114350E+09 | -1.406200E+01 | 6.489300E+01 | -3.487000E+00 | -4.574800E+01 |
| 5.163700E+09 | -1.348300E+01 | 5.962000E+01 | -3.646000E+00 | -6.604200E+01 |
| 5.213050E+09 | -1.291300E+01 | 5.426100E+01 | -3.857000E+00 | -8.659800E+01 |
| 5.262400E+09 | -1.238600E+01 | 4.884800E+01 | -4.123000E+00 | -1.073300E+02 |
| 5.311750E+09 | -1.190800E+01 | 4.356100E+01 | -4.422000E+00 | -1.281600E+02 |
| 5.361100E+09 | -1.147400E+01 | 3.849100E+01 | -4.760000E+00 | -1.491800E+02 |

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|---|---|---|---|---|
| 5.410450E+09 | -1.105200E+01 | 3.399000E+01 | -5.146000E+00 | -1.704200E+02 |
| 5.459800E+09 | -1.060200E+01 | 3.006500E+01 | -5.598000E+00 | 1.680200E+02 |
| 5.509150E+09 | -1.004100E+01 | 2.691400E+01 | -6.101000E+00 | 1.462200E+02 |
| 5.558500E+09 | -9.173000E+00 | 2.360400E+01 | -6.658000E+00 | 1.243100E+02 |
| 5.607850E+09 | -8.126000E+00 | 1.794300E+01 | -7.294000E+00 | 1.017100E+02 |
| 5.657200E+09 | -7.223000E+00 | 1.017900E+01 | -8.118000E+00 | 7.919800E+01 |
| 5.706550E+09 | -6.564000E+00 | 1.678200E+00 | -8.984000E+00 | 5.706700E+01 |
| 5.755900E+09 | -6.064000E+00 | -6.771700E+00 | -9.895000E+00 | 3.471700E+01 |
| 5.805250E+09 | -5.657000E+00 | -1.511200E+01 | -1.096100E+01 | 1.288800E+01 |
| 5.854600E+09 | -5.302000E+00 | -2.330300E+01 | -1.199000E+01 | -8.333100E+00 |
| 5.903950E+09 | -4.962000E+00 | -3.145800E+01 | -1.303500E+01 | -2.932000E+01 |
| 5.953300E+09 | -4.609000E+00 | -3.977600E+01 | -1.410100E+01 | -5.026800E+01 |
| 6.002650E+09 | -4.228000E+00 | -4.862500E+01 | -1.505200E+01 | -6.981500E+01 |
| 6.052000E+09 | -3.848000E+00 | -5.838400E+01 | -1.590600E+01 | -8.912800E+01 |
| 6.101350E+09 | -3.538000E+00 | -6.923900E+01 | -1.666500E+01 | -1.083000E+02 |
| 6.150700E+09 | -3.351000E+00 | -8.100500E+01 | -1.731000E+01 | -1.256200E+02 |
| 6.200050E+09 | -3.294000E+00 | -9.340700E+01 | -1.764800E+01 | -1.434700E+02 |
| 6.249400E+09 | -3.353000E+00 | -1.063600E+02 | -1.780900E+01 | -1.603800E+02 |
| 6.298750E+09 | -3.505000E+00 | -1.198700E+02 | -1.771400E+01 | -1.772700E+02 |
| 6.348100E+09 | -3.737000E+00 | -1.340300E+02 | -1.741400E+01 | 1.652100E+02 |
| 6.397450E+09 | -4.035000E+00 | -1.489600E+02 | -1.700100E+01 | 1.482300E+02 |
| 6.446800E+09 | -4.391000E+00 | -1.647000E+02 | -1.640400E+01 | 1.301300E+02 |
| 6.496150E+09 | -4.805000E+00 | 1.787100E+02 | -1.566500E+01 | 1.127900E+02 |
| 6.545500E+09 | -5.272000E+00 | 1.612700E+02 | -1.491300E+01 | 9.395100E+01 |
| 6.594850E+09 | -5.784000E+00 | 1.430900E+02 | -1.413400E+01 | 7.544300E+01 |
| 6.644200E+09 | -6.346000E+00 | 1.244500E+02 | -1.325800E+01 | 5.717100E+01 |
| 6.693550E+09 | -6.974000E+00 | 1.054900E+02 | -1.242100E+01 | 3.749800E+01 |
| 6.742900E+09 | -7.682000E+00 | 8.669900E+01 | -1.158400E+01 | 1.841000E+01 |
| 6.792250E+09 | -8.476000E+00 | 6.856200E+01 | -1.081800E+01 | -1.517500E+00 |
| 6.841600E+09 | -9.340000E+00 | 5.183400E+01 | -1.010500E+01 | -2.127000E+01 |
| 6.890950E+09 | -1.017800E+01 | 3.728600E+01 | -9.395000E+00 | -4.121700E+01 |
| 6.940300E+09 | -1.084300E+01 | 2.488100E+01 | -8.796000E+00 | -6.214400E+01 |
| 6.989650E+09 | -1.131500E+01 | 1.399900E+01 | -8.242000E+00 | -8.202300E+01 |
| 7.039000E+09 | -1.158500E+01 | 4.198200E+00 | -7.828000E+00 | -1.030600E+02 |
| 7.088350E+09 | -1.170900E+01 | -4.681500E+00 | -7.399000E+00 | -1.229000E+02 |
| 7.137700E+09 | -1.172700E+01 | -1.271700E+01 | -7.048000E+00 | -1.435500E+02 |
| 7.187050E+09 | -1.167500E+01 | -2.015700E+01 | -6.904000E+00 | -1.640400E+02 |
| 7.236400E+09 | -1.157400E+01 | -2.696200E+01 | -6.611000E+00 | 1.759700E+02 |
| 7.285750E+09 | -1.144400E+01 | -3.329500E+01 | -6.475000E+00 | 1.557600E+02 |
| 7.335100E+09 | -1.131700E+01 | -3.903300E+01 | -6.365000E+00 | 1.360200E+02 |
| 7.384450E+09 | -1.118100E+01 | -4.419700E+01 | -6.282000E+00 | 1.163600E+02 |
| 7.433800E+09 | -1.100400E+01 | -4.888800E+01 | -6.169000E+00 | 9.685000E+01 |
| 7.483150E+09 | -1.077900E+01 | -5.351600E+01 | -6.137000E+00 | 7.683300E+01 |
| 7.532500E+09 | -1.053700E+01 | -5.815100E+01 | -6.220000E+00 | 5.747600E+01 |
| 7.581850E+09 | -1.031600E+01 | -6.272400E+01 | -6.094000E+00 | 3.901500E+01 |
| 7.631200E+09 | -1.011700E+01 | -6.720300E+01 | -6.164000E+00 | 1.864100E+01 |
| 7.680550E+09 | -9.931000E+00 | -7.159400E+01 | -6.322000E+00 | -1.524400E-01 |
| 7.729900E+09 | -9.768000E+00 | -7.582100E+01 | -6.221000E+00 | -1.939000E+01 |
| 7.779250E+09 | -9.629000E+00 | -7.988300E+01 | -6.417000E+00 | -3.854000E+01 |

| | | | | |
|---|---|---|---|---|
| 7.828600E+09 | -9.529000E+00 | -8.363600E+01 | -6.410000E+00 | -5.712800E+01 |
| 7.877950E+09 | -9.411000E+00 | -8.686100E+01 | -6.413000E+00 | -7.718000E+01 |
| 7.927300E+09 | -9.189000E+00 | -8.958000E+01 | -6.625000E+00 | -9.717300E+01 |
| 7.976650E+09 | -8.839000E+00 | -9.286200E+01 | -6.779000E+00 | -1.164400E+02 |
| 8.026000E+09 | -8.517000E+00 | -9.685300E+01 | -6.823000E+00 | -1.366000E+02 |
| 8.075350E+09 | -8.248000E+00 | -1.012700E+02 | -7.104000E+00 | -1.576700E+02 |
| 8.124700E+09 | -8.056000E+00 | -1.058000E+02 | -7.621000E+00 | -1.776200E+02 |
| 8.174050E+09 | -7.913000E+00 | -1.102200E+02 | -7.724000E+00 | 1.627700E+02 |
| 8.223400E+09 | -7.824000E+00 | -1.144400E+02 | -8.005000E+00 | 1.409300E+02 |
| 8.272750E+09 | -7.751000E+00 | -1.182600E+02 | -8.662000E+00 | 1.202000E+02 |
| 8.322100E+09 | -7.649000E+00 | -1.215200E+02 | -8.981000E+00 | 9.998400E+01 |
| 8.371450E+09 | -7.406000E+00 | -1.245800E+02 | -9.477000E+00 | 7.742900E+01 |
| 8.420800E+09 | -7.005000E+00 | -1.282500E+02 | -1.016100E+01 | 5.558500E+01 |
| 8.470150E+09 | -6.544000E+00 | -1.334300E+02 | -1.079500E+01 | 3.399600E+01 |
| 8.519500E+09 | -6.183000E+00 | -1.398600E+02 | -1.158500E+01 | 1.172400E+01 |
| 8.568850E+09 | -5.941000E+00 | -1.470000E+02 | -1.250000E+01 | -8.447100E+00 |
| 8.618200E+09 | -5.803000E+00 | -1.544800E+02 | -1.308600E+01 | -3.030200E+01 |
| 8.667550E+09 | -5.728000E+00 | -1.623000E+02 | -1.386900E+01 | -5.302100E+01 |
| 8.716900E+09 | -5.709000E+00 | -1.706200E+02 | -1.487700E+01 | -7.345000E+01 |
| 8.766250E+09 | -5.730000E+00 | -1.797100E+02 | -1.546500E+01 | -9.429700E+01 |
| 8.815600E+09 | -5.789000E+00 | 1.700700E+02 | -1.617500E+01 | -1.156900E+02 |
| 8.864950E+09 | -5.906000E+00 | 1.580900E+02 | -1.688300E+01 | -1.373700E+02 |
| 8.914300E+09 | -6.127000E+00 | 1.440300E+02 | -1.753100E+01 | -1.579600E+02 |
| 8.963650E+09 | -6.452000E+00 | 1.276400E+02 | -1.810400E+01 | -1.783600E+02 |
| 9.013000E+09 | -6.834000E+00 | 1.092300E+02 | -1.849900E+01 | 1.611300E+02 |
| 9.062350E+09 | -7.203000E+00 | 8.922300E+01 | -1.884900E+01 | 1.398500E+02 |
| 9.111700E+09 | -7.511000E+00 | 6.817700E+01 | -1.928100E+01 | 1.182300E+02 |
| 9.161050E+09 | -7.742000E+00 | 4.643400E+01 | -1.961600E+01 | 9.848800E+01 |
| 9.210400E+09 | -7.887000E+00 | 2.444200E+01 | -1.975300E+01 | 7.707700E+01 |
| 9.259750E+09 | -7.939000E+00 | 2.476000E+00 | -1.997900E+01 | 5.469500E+01 |
| 9.309100E+09 | -7.899000E+00 | -1.910800E+01 | -2.033800E+01 | 3.372500E+01 |
| 9.358450E+09 | -7.757000E+00 | -4.009000E+01 | -2.042800E+01 | 1.316000E+01 |
| 9.407800E+09 | -7.518000E+00 | -5.995200E+01 | -2.045700E+01 | -8.394900E+00 |
| 9.457150E+09 | -7.199000E+00 | -7.835600E+01 | -2.066100E+01 | -3.012700E+01 |
| 9.506500E+09 | -6.850000E+00 | -9.475200E+01 | -2.065600E+01 | -5.065500E+01 |
| 9.555850E+09 | -6.529000E+00 | -1.090300E+02 | -2.052100E+01 | -7.166900E+01 |
| 9.605200E+09 | -6.295000E+00 | -1.211700E+02 | -2.031400E+01 | -9.274000E+01 |
| 9.654550E+09 | -6.152000E+00 | -1.314600E+02 | -1.994600E+01 | -1.145600E+02 |
| 9.703900E+09 | -6.090000E+00 | -1.402000E+02 | -1.962600E+01 | -1.361500E+02 |
| 9.753250E+09 | -6.075000E+00 | -1.478100E+02 | -1.905200E+01 | -1.571800E+02 |
| 9.802600E+09 | -6.112000E+00 | -1.541000E+02 | -1.846900E+01 | -1.768800E+02 |
| 9.851950E+09 | -6.177000E+00 | -1.592700E+02 | -1.788600E+01 | 1.654200E+02 |
| 9.901300E+09 | -6.266000E+00 | -1.633700E+02 | -1.725200E+01 | 1.486600E+02 |
| 9.950650E+09 | -6.356000E+00 | -1.665900E+02 | -1.686200E+01 | 1.342700E+02 |
| 1.000000E+10 | -6.440000E+00 | -1.689500E+02 | -1.630700E+01 | 1.229100E+02 |

## A.5. 130-mil wide 6-turn structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.774700E+01 | -1.766300E+02 | -1.890000E-01 | -7.677900E+01 |
| 1.793500E+08 | -1.809200E+01 | 1.724900E+02 | -2.020000E-01 | -8.714800E+01 |
| 2.287000E+08 | -1.913600E+01 | 1.603000E+02 | -2.140000E-01 | -9.926800E+01 |
| 2.780500E+08 | -2.065500E+01 | 1.585300E+02 | -2.310000E-01 | -1.131700E+02 |
| 3.274000E+08 | -2.115700E+01 | 1.568600E+02 | -2.500000E-01 | -1.288400E+02 |
| 3.767500E+08 | -2.125800E+01 | 1.537200E+02 | -2.750000E-01 | -1.462700E+02 |
| 4.261000E+08 | -2.116300E+01 | 1.488600E+02 | -3.030000E-01 | -1.654400E+02 |
| 4.754500E+08 | -2.113000E+01 | 1.440200E+02 | -3.340000E-01 | 1.753100E+02 |
| 5.248000E+08 | -2.113400E+01 | 1.392900E+02 | -3.700000E-01 | 1.560600E+02 |
| 5.741500E+08 | -2.116700E+01 | 1.347700E+02 | -3.860000E-01 | 1.367300E+02 |
| 6.235000E+08 | -2.127200E+01 | 1.304300E+02 | -4.150000E-01 | 1.173400E+02 |
| 6.728500E+08 | -2.146300E+01 | 1.263000E+02 | -4.450000E-01 | 9.788100E+01 |
| 7.222000E+08 | -2.177300E+01 | 1.228500E+02 | -4.700000E-01 | 7.836100E+01 |
| 7.715500E+08 | -2.207100E+01 | 1.247600E+02 | -4.990000E-01 | 5.876700E+01 |
| 8.209000E+08 | -2.120800E+01 | 1.205300E+02 | -5.260000E-01 | 3.911000E+01 |
| 8.702500E+08 | -2.092100E+01 | 1.154500E+02 | -5.560000E-01 | 1.938700E+01 |
| 9.196000E+08 | -2.080900E+01 | 1.102900E+02 | -5.860000E-01 | -3.762800E-01 |
| 9.689500E+08 | -2.077400E+01 | 1.051400E+02 | -6.220000E-01 | -2.027900E+01 |
| 1.018300E+09 | -2.079900E+01 | 1.001200E+02 | -6.400000E-01 | -4.021700E+01 |
| 1.067650E+09 | -2.089900E+01 | 9.521000E+01 | -6.550000E-01 | -6.027400E+01 |
| 1.117000E+09 | -2.110200E+01 | 9.047700E+01 | -6.980000E-01 | -8.037900E+01 |
| 1.166350E+09 | -2.140300E+01 | 8.602400E+01 | -7.160000E-01 | -1.005900E+02 |
| 1.215700E+09 | -2.187700E+01 | 8.267200E+01 | -7.410000E-01 | -1.209100E+02 |
| 1.265050E+09 | -2.224600E+01 | 8.393600E+01 | -7.700000E-01 | -1.413100E+02 |
| 1.314400E+09 | -2.154600E+01 | 8.380900E+01 | -8.030000E-01 | -1.617900E+02 |
| 1.363750E+09 | -2.117000E+01 | 7.870200E+01 | -8.320000E-01 | 1.776400E+02 |
| 1.413100E+09 | -2.106200E+01 | 7.291800E+01 | -8.650000E-01 | 1.570100E+02 |
| 1.462450E+09 | -2.108900E+01 | 6.705000E+01 | -8.890000E-01 | 1.361800E+02 |
| 1.511800E+09 | -2.124500E+01 | 6.128900E+01 | -9.150000E-01 | 1.153400E+02 |
| 1.561150E+09 | -2.152000E+01 | 5.565000E+01 | -9.460000E-01 | 9.446300E+01 |
| 1.610500E+09 | -2.191700E+01 | 5.008700E+01 | -9.810000E-01 | 7.340100E+01 |
| 1.659850E+09 | -2.240700E+01 | 4.481700E+01 | -1.003000E+00 | 5.220000E+01 |
| 1.709200E+09 | -2.301300E+01 | 4.056000E+01 | -1.042000E+00 | 3.095700E+01 |
| 1.758550E+09 | -2.360800E+01 | 3.799100E+01 | -1.072000E+00 | 9.597900E+00 |
| 1.807900E+09 | -2.394700E+01 | 3.443700E+01 | -1.106000E+00 | -1.183500E+01 |
| 1.857250E+09 | -2.442600E+01 | 2.878000E+01 | -1.134000E+00 | -3.339400E+01 |
| 1.906600E+09 | -2.511700E+01 | 2.326900E+01 | -1.170000E+00 | -5.501400E+01 |
| 1.955950E+09 | -2.587900E+01 | 1.798900E+01 | -1.198000E+00 | -7.677100E+01 |
| 2.005300E+09 | -2.666200E+01 | 1.320100E+01 | -1.232000E+00 | -9.852100E+01 |
| 2.054650E+09 | -2.734100E+01 | 7.638200E+00 | -1.258000E+00 | -1.204600E+02 |
| 2.104000E+09 | -2.784100E+01 | 9.475700E-01 | -1.301000E+00 | -1.426100E+02 |
| 2.153350E+09 | -2.795100E+01 | -6.803300E+00 | -1.328000E+00 | -1.647200E+02 |
| 2.202700E+09 | -2.769400E+01 | -1.629300E+01 | -1.373000E+00 | 1.729200E+02 |
| 2.252050E+09 | -2.692400E+01 | -2.767600E+01 | -1.416000E+00 | 1.504500E+02 |
| 2.301400E+09 | -2.564000E+01 | -4.258200E+01 | -1.475000E+00 | 1.278900E+02 |

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|---|---|---|---|---|
| 2.350750E+09 | -2.427400E+01 | -6.177800E+01 | -1.558000E+00 | 1.051200E+02 |
| 2.400100E+09 | -2.323000E+01 | -8.274100E+01 | -1.648000E+00 | 8.221100E+01 |
| 2.449450E+09 | -2.250500E+01 | -1.023200E+02 | -1.774000E+00 | 5.903400E+01 |
| 2.498800E+09 | -2.163600E+01 | -1.188300E+02 | -1.905000E+00 | 3.578500E+01 |
| 2.548150E+09 | -2.038400E+01 | -1.342800E+02 | -2.111000E+00 | 1.216700E+01 |
| 2.597500E+09 | -1.888400E+01 | -1.486400E+02 | -2.368000E+00 | -1.151900E+01 |
| 2.646850E+09 | -1.724800E+01 | -1.619100E+02 | -2.654000E+00 | -3.536900E+01 |
| 2.696200E+09 | -1.566900E+01 | -1.742200E+02 | -3.113000E+00 | -5.935400E+01 |
| 2.745550E+09 | -1.411000E+01 | 1.747900E+02 | -3.461000E+00 | -8.273500E+01 |
| 2.794900E+09 | -1.264200E+01 | 1.645400E+02 | -4.143000E+00 | -1.066900E+02 |
| 2.844250E+09 | -1.122000E+01 | 1.550800E+02 | -4.825000E+00 | -1.286100E+02 |
| 2.893600E+09 | -9.771000E+00 | 1.459500E+02 | -5.389000E+00 | -1.507900E+02 |
| 2.942950E+09 | -8.223000E+00 | 1.367300E+02 | -6.219000E+00 | -1.723500E+02 |
| 2.992300E+09 | -6.496000E+00 | 1.254500E+02 | -6.827000E+00 | 1.679600E+02 |
| 3.041650E+09 | -5.009000E+00 | 1.110600E+02 | -7.494000E+00 | 1.486200E+02 |
| 3.091000E+09 | -3.980000E+00 | 9.552200E+01 | -7.977000E+00 | 1.304900E+02 |
| 3.140350E+09 | -3.304000E+00 | 7.998500E+01 | -8.477000E+00 | 1.129600E+02 |
| 3.189700E+09 | -2.889000E+00 | 6.473400E+01 | -8.758000E+00 | 9.662500E+01 |
| 3.239050E+09 | -2.678000E+00 | 4.976800E+01 | -8.777000E+00 | 8.009300E+01 |
| 3.288400E+09 | -2.656000E+00 | 3.496300E+01 | -8.846000E+00 | 6.433000E+01 |
| 3.337750E+09 | -2.815000E+00 | 2.010500E+01 | -8.467000E+00 | 4.877700E+01 |
| 3.387100E+09 | -3.206000E+00 | 5.062000E+00 | -8.022000E+00 | 3.193000E+01 |
| 3.436450E+09 | -3.892000E+00 | -1.012900E+01 | -7.509000E+00 | 1.498900E+01 |
| 3.485800E+09 | -5.044000E+00 | -2.500100E+01 | -6.768000E+00 | -2.547500E+00 |
| 3.535150E+09 | -6.740000E+00 | -3.709000E+01 | -6.160000E+00 | -2.153500E+01 |
| 3.584500E+09 | -8.435000E+00 | -4.431100E+01 | -5.456000E+00 | -4.076300E+01 |
| 3.633850E+09 | -9.807000E+00 | -4.986700E+01 | -4.854000E+00 | -6.105900E+01 |
| 3.683200E+09 | -1.103100E+01 | -5.524300E+01 | -4.215000E+00 | -8.161500E+01 |
| 3.732550E+09 | -1.220400E+01 | -6.062700E+01 | -3.733000E+00 | -1.028700E+02 |
| 3.781900E+09 | -1.340500E+01 | -6.613400E+01 | -3.337000E+00 | -1.235800E+02 |
| 3.831250E+09 | -1.466500E+01 | -7.164900E+01 | -2.988000E+00 | -1.454700E+02 |
| 3.880600E+09 | -1.607400E+01 | -7.714900E+01 | -2.762000E+00 | -1.666400E+02 |
| 3.929950E+09 | -1.760100E+01 | -8.257700E+01 | -2.575000E+00 | 1.717100E+02 |
| 3.979300E+09 | -1.929100E+01 | -8.903300E+01 | -2.553000E+00 | 1.508000E+02 |
| 4.028650E+09 | -2.097700E+01 | -9.858200E+01 | -2.475000E+00 | 1.301900E+02 |
| 4.078000E+09 | -2.196500E+01 | -1.158100E+02 | -2.456000E+00 | 1.095900E+02 |
| 4.127350E+09 | -2.269100E+01 | -1.397900E+02 | -2.460000E+00 | 8.921300E+01 |
| 4.176700E+09 | -2.352700E+01 | -1.659800E+02 | -2.475000E+00 | 6.914000E+01 |
| 4.226050E+09 | -2.448300E+01 | 1.667800E+02 | -2.471000E+00 | 4.904400E+01 |
| 4.275400E+09 | -2.567000E+01 | 1.398100E+02 | -2.477000E+00 | 2.895000E+01 |
| 4.324750E+09 | -2.729000E+01 | 1.125700E+02 | -2.495000E+00 | 8.686100E+00 |
| 4.374100E+09 | -2.914500E+01 | 1.018300E+02 | -2.520000E+00 | -1.145200E+01 |
| 4.423450E+09 | -2.959500E+01 | 9.078600E+01 | -2.549000E+00 | -3.172900E+01 |
| 4.472800E+09 | -2.929600E+01 | 7.967400E+01 | -2.588000E+00 | -5.204800E+01 |
| 4.522150E+09 | -2.827400E+01 | 6.952800E+01 | -2.627000E+00 | -7.256700E+01 |
| 4.571500E+09 | -2.662500E+01 | 6.177200E+01 | -2.700000E+00 | -9.314100E+01 |
| 4.620850E+09 | -2.505000E+01 | 5.856400E+01 | -2.771000E+00 | -1.137200E+02 |
| 4.670200E+09 | -2.373500E+01 | 5.702500E+01 | -2.847000E+00 | -1.345200E+02 |

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|---|---|---|---|---|
| 4.719550E+09 | -2.272300E+01 | 5.612100E+01 | -2.927000E+00 | -1.553300E+02 |
| 4.768900E+09 | -2.191500E+01 | 5.684300E+01 | -2.991000E+00 | -1.763800E+02 |
| 4.818250E+09 | -2.110800E+01 | 6.004400E+01 | -3.079000E+00 | 1.622500E+02 |
| 4.867600E+09 | -1.958700E+01 | 6.720200E+01 | -3.181000E+00 | 1.407500E+02 |
| 4.916950E+09 | -1.735000E+01 | 5.941300E+01 | -3.278000E+00 | 1.189200E+02 |
| 4.966300E+09 | -1.601700E+01 | 5.242800E+01 | -3.402000E+00 | 9.677000E+01 |
| 5.015650E+09 | -1.501800E+01 | 4.566700E+01 | -3.557000E+00 | 7.437900E+01 |
| 5.065000E+09 | -1.428400E+01 | 3.918800E+01 | -3.731000E+00 | 5.186800E+01 |
| 5.114350E+09 | -1.377800E+01 | 3.327200E+01 | -3.897000E+00 | 2.906700E+01 |
| 5.163700E+09 | -1.350200E+01 | 2.836500E+01 | -4.072000E+00 | 5.740400E+00 |
| 5.213050E+09 | -1.334700E+01 | 2.561700E+01 | -4.281000E+00 | -1.802000E+01 |
| 5.262400E+09 | -1.297400E+01 | 2.515000E+01 | -4.534000E+00 | -4.232600E+01 |
| 5.311750E+09 | -1.217300E+01 | 2.508900E+01 | -4.855000E+00 | -6.705000E+01 |
| 5.361100E+09 | -1.100400E+01 | 2.267600E+01 | -5.256000E+00 | -9.217300E+01 |
| 5.410450E+09 | -9.970000E+00 | 1.704700E+01 | -5.744000E+00 | -1.174900E+02 |
| 5.459800E+09 | -9.259000E+00 | 1.049500E+01 | -6.320000E+00 | -1.430500E+02 |
| 5.509150E+09 | -8.786000E+00 | 4.368400E+00 | -6.960000E+00 | -1.688300E+02 |
| 5.558500E+09 | -8.406000E+00 | -7.099900E-01 | -7.677000E+00 | 1.652000E+02 |
| 5.607850E+09 | -7.987000E+00 | -4.960300E+00 | -8.534000E+00 | 1.383800E+02 |
| 5.657200E+09 | -7.450000E+00 | -8.763000E+00 | -9.672000E+00 | 1.117000E+02 |
| 5.706550E+09 | -6.712000E+00 | -1.283600E+01 | -1.094400E+01 | 8.563200E+01 |
| 5.755900E+09 | -5.817000E+00 | -1.855600E+01 | -1.237200E+01 | 5.972400E+01 |
| 5.805250E+09 | -5.026000E+00 | -2.639300E+01 | -1.405700E+01 | 3.529200E+01 |
| 5.854600E+09 | -4.467000E+00 | -3.507000E+01 | -1.572000E+01 | 1.208900E+01 |
| 5.903950E+09 | -4.065000E+00 | -4.379800E+01 | -1.745000E+01 | -1.011000E+01 |
| 5.953300E+09 | -3.749000E+00 | -5.244700E+01 | -1.917000E+01 | -3.161200E+01 |
| 6.002650E+09 | -3.468000E+00 | -6.122700E+01 | -2.070600E+01 | -5.153800E+01 |
| 6.052000E+09 | -3.211000E+00 | -7.041800E+01 | -2.208900E+01 | -7.128100E+01 |
| 6.101350E+09 | -3.003000E+00 | -8.041000E+01 | -2.331800E+01 | -9.099800E+01 |
| 6.150700E+09 | -2.897000E+00 | -9.120700E+01 | -2.430500E+01 | -1.091400E+02 |
| 6.200050E+09 | -2.908000E+00 | -1.027200E+02 | -2.487500E+01 | -1.281500E+02 |
| 6.249400E+09 | -3.041000E+00 | -1.149500E+02 | -2.513300E+01 | -1.466700E+02 |
| 6.298750E+09 | -3.287000E+00 | -1.279700E+02 | -2.500300E+01 | -1.655600E+02 |
| 6.348100E+09 | -3.642000E+00 | -1.419400E+02 | -2.453500E+01 | 1.741800E+02 |
| 6.397450E+09 | -4.094000E+00 | -1.571400E+02 | -2.380800E+01 | 1.540200E+02 |
| 6.446800E+09 | -4.635000E+00 | -1.737300E+02 | -2.281300E+01 | 1.320100E+02 |
| 6.496150E+09 | -5.243000E+00 | 1.681500E+02 | -2.158400E+01 | 1.100800E+02 |
| 6.545500E+09 | -5.890000E+00 | 1.486300E+02 | -2.035600E+01 | 8.639500E+01 |
| 6.594850E+09 | -6.566000E+00 | 1.279400E+02 | -1.907000E+01 | 6.293200E+01 |
| 6.644200E+09 | -7.280000E+00 | 1.066100E+02 | -1.767300E+01 | 3.959700E+01 |
| 6.693550E+09 | -8.044000E+00 | 8.521000E+01 | -1.633400E+01 | 1.521500E+01 |
| 6.742900E+09 | -8.854000E+00 | 6.454100E+01 | -1.502400E+01 | -8.660000E+00 |
| 6.792250E+09 | -9.636000E+00 | 4.545000E+01 | -1.384600E+01 | -3.331100E+01 |
| 6.841600E+09 | -1.025500E+01 | 2.816300E+01 | -1.277400E+01 | -5.755900E+01 |
| 6.890950E+09 | -1.065800E+01 | 1.232300E+01 | -1.175700E+01 | -8.194800E+01 |
| 6.940300E+09 | -1.086500E+01 | -2.114900E+00 | -1.095500E+01 | -1.069200E+02 |
| 6.989650E+09 | -1.092600E+01 | -1.514500E+01 | -1.016700E+01 | -1.306500E+02 |
| 7.039000E+09 | -1.090900E+01 | -2.661200E+01 | -9.620000E+00 | -1.551600E+02 |

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|---|---|---|---|---|
| 7.088350E+09 | -1.087400E+01 | -3.649200E+01 | -9.011000E+00 | -1.786500E+02 |
| 7.137700E+09 | -1.086000E+01 | -4.458900E+01 | -8.556000E+00 | 1.573900E+02 |
| 7.187050E+09 | -1.084300E+01 | -5.083500E+01 | -8.298000E+00 | 1.338100E+02 |
| 7.236400E+09 | -1.073200E+01 | -5.536700E+01 | -7.962000E+00 | 1.106200E+02 |
| 7.285750E+09 | -1.044000E+01 | -5.906500E+01 | -7.764000E+00 | 8.733000E+01 |
| 7.335100E+09 | -1.000200E+01 | -6.303000E+01 | -7.670000E+00 | 6.460200E+01 |
| 7.384450E+09 | -9.563000E+00 | -6.770900E+01 | -7.583000E+00 | 4.211300E+01 |
| 7.433800E+09 | -9.205000E+00 | -7.273100E+01 | -7.473000E+00 | 1.980400E+01 |
| 7.483150E+09 | -8.950000E+00 | -7.774900E+01 | -7.505000E+00 | -2.823500E+00 |
| 7.532500E+09 | -8.791000E+00 | -8.258600E+01 | -7.571000E+00 | -2.435500E+01 |
| 7.581850E+09 | -8.721000E+00 | -8.693100E+01 | -7.376000E+00 | -4.600000E+01 |
| 7.631200E+09 | -8.710000E+00 | -9.036100E+01 | -7.441000E+00 | -6.869900E+01 |
| 7.680550E+09 | -8.639000E+00 | -9.272000E+01 | -7.500000E+00 | -9.068300E+01 |
| 7.729900E+09 | -8.400000E+00 | -9.476900E+01 | -7.423000E+00 | -1.131500E+02 |
| 7.779250E+09 | -8.054000E+00 | -9.753700E+01 | -7.624000E+00 | -1.359100E+02 |
| 7.828600E+09 | -7.722000E+00 | -1.011200E+02 | -7.697000E+00 | -1.576400E+02 |
| 7.877950E+09 | -7.478000E+00 | -1.051900E+02 | -7.729000E+00 | 1.791500E+02 |
| 7.927300E+09 | -7.335000E+00 | -1.093000E+02 | -8.053000E+00 | 1.564800E+02 |
| 7.976650E+09 | -7.284000E+00 | -1.130500E+02 | -8.178000E+00 | 1.345900E+02 |
| 8.026000E+09 | -7.275000E+00 | -1.161800E+02 | -8.185000E+00 | 1.113600E+02 |
| 8.075350E+09 | -7.234000E+00 | -1.184000E+02 | -8.443000E+00 | 8.722600E+01 |
| 8.124700E+09 | -7.047000E+00 | -1.201500E+02 | -8.926000E+00 | 6.427300E+01 |
| 8.174050E+09 | -6.686000E+00 | -1.222900E+02 | -9.069000E+00 | 4.100000E+01 |
| 8.223400E+09 | -6.256000E+00 | -1.256900E+02 | -9.481000E+00 | 1.610200E+01 |
| 8.272750E+09 | -5.904000E+00 | -1.301600E+02 | -1.024300E+01 | -7.373200E+00 |
| 8.322100E+09 | -5.684000E+00 | -1.350300E+02 | -1.059900E+01 | -2.961200E+01 |
| 8.371450E+09 | -5.561000E+00 | -1.398100E+02 | -1.112100E+01 | -5.478300E+01 |
| 8.420800E+09 | -5.488000E+00 | -1.442400E+02 | -1.180000E+01 | -7.917400E+01 |
| 8.470150E+09 | -5.389000E+00 | -1.483700E+02 | -1.238500E+01 | -1.043000E+02 |
| 8.519500E+09 | -5.222000E+00 | -1.526600E+02 | -1.331900E+01 | -1.303800E+02 |
| 8.568850E+09 | -5.002000E+00 | -1.576300E+02 | -1.436500E+01 | -1.546300E+02 |
| 8.618200E+09 | -4.794000E+00 | -1.637400E+02 | -1.529800E+01 | 1.789900E+02 |
| 8.667550E+09 | -4.685000E+00 | -1.710100E+02 | -1.648200E+01 | 1.525300E+02 |
| 8.716900E+09 | -4.729000E+00 | -1.792300E+02 | -1.781900E+01 | 1.281500E+02 |
| 8.766250E+09 | -4.946000E+00 | 1.716800E+02 | -1.880600E+01 | 1.032500E+02 |
| 8.815600E+09 | -5.362000E+00 | 1.615400E+02 | -1.979900E+01 | 7.787000E+01 |
| 8.864950E+09 | -5.990000E+00 | 1.498100E+02 | -2.086900E+01 | 5.147900E+01 |
| 8.914300E+09 | -6.828000E+00 | 1.353800E+02 | -2.188300E+01 | 2.658400E+01 |
| 8.963650E+09 | -7.685000E+00 | 1.170200E+02 | -2.276700E+01 | 2.274200E+00 |
| 9.013000E+09 | -8.376000E+00 | 9.547000E+01 | -2.342300E+01 | -2.197700E+01 |
| 9.062350E+09 | -8.876000E+00 | 7.212300E+01 | -2.398100E+01 | -4.643400E+01 |
| 9.111700E+09 | -9.223000E+00 | 4.792200E+01 | -2.449100E+01 | -7.043100E+01 |
| 9.161050E+09 | -9.429000E+00 | 2.336200E+01 | -2.477900E+01 | -9.253400E+01 |
| 9.210400E+09 | -9.512000E+00 | -1.207100E+00 | -2.486600E+01 | -1.159900E+02 |
| 9.259750E+09 | -9.459000E+00 | -2.550900E+01 | -2.500000E+01 | -1.399400E+02 |
| 9.309100E+09 | -9.252000E+00 | -4.918900E+01 | -2.516700E+01 | -1.620600E+02 |
| 9.358450E+09 | -8.854000E+00 | -7.187500E+01 | -2.508300E+01 | 1.760700E+02 |
| 9.407800E+09 | -8.224000E+00 | -9.296400E+01 | -2.491000E+01 | 1.535700E+02 |

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|---|---|---|---|---|
| 9.457150E+09 | -7.368000E+00 | -1.113900E+02 | -2.488100E+01 | 1.309400E+02 |
| 9.506500E+09 | -6.485000E+00 | -1.259900E+02 | -2.468700E+01 | 1.088000E+02 |
| 9.555850E+09 | -5.795000E+00 | -1.374300E+02 | -2.442300E+01 | 8.607100E+01 |
| 9.605200E+09 | -5.328000E+00 | -1.467400E+02 | -2.410100E+01 | 6.274400E+01 |
| 9.654550E+09 | -5.025000E+00 | -1.546700E+02 | -2.372800E+01 | 3.792800E+01 |
| 9.703900E+09 | -4.848000E+00 | -1.615300E+02 | -2.340300E+01 | 1.303900E+01 |
| 9.753250E+09 | -4.758000E+00 | -1.676000E+02 | -2.282900E+01 | -1.203100E+01 |
| 9.802600E+09 | -4.729000E+00 | -1.726800E+02 | -2.228000E+01 | -3.568100E+01 |
| 9.851950E+09 | -4.741000E+00 | -1.769000E+02 | -2.174400E+01 | -5.729800E+01 |
| 9.901300E+09 | -4.774000E+00 | 1.796600E+02 | -2.119900E+01 | -7.784200E+01 |
| 9.950650E+09 | -4.812000E+00 | 1.769200E+02 | -2.089000E+01 | -9.562000E+01 |
| 1.000000E+10 | -4.847000E+00 | 1.747700E+02 | -2.040800E+01 | -1.103700E+02 |

## A.6. 130-mil wide 7-turn structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.767400E+01 | 1.760500E+02 | -1.730000E-01 | -8.619500E+01 |
| 1.793500E+08 | -1.919700E+01 | 1.661800E+02 | -1.830000E-01 | -9.787300E+01 |
| 2.287000E+08 | -2.016100E+01 | 1.674500E+02 | -1.950000E-01 | -1.115300E+02 |
| 2.780500E+08 | -2.054100E+01 | 1.668100E+02 | -2.140000E-01 | -1.271700E+02 |
| 3.274000E+08 | -2.062100E+01 | 1.642800E+02 | -2.360000E-01 | -1.448000E+02 |
| 3.767500E+08 | -2.055300E+01 | 1.596200E+02 | -2.680000E-01 | -1.643900E+02 |
| 4.261000E+08 | -2.046200E+01 | 1.530700E+02 | -2.950000E-01 | 1.740700E+02 |
| 4.754500E+08 | -2.055700E+01 | 1.462800E+02 | -3.300000E-01 | 1.524700E+02 |
| 5.248000E+08 | -2.086500E+01 | 1.395000E+02 | -3.600000E-01 | 1.308300E+02 |
| 5.741500E+08 | -2.138400E+01 | 1.327700E+02 | -3.810000E-01 | 1.090700E+02 |
| 6.235000E+08 | -2.269300E+01 | 1.274200E+02 | -4.090000E-01 | 8.725500E+01 |
| 6.728500E+08 | -2.328400E+01 | 1.338100E+02 | -4.420000E-01 | 6.535600E+01 |
| 7.222000E+08 | -2.218700E+01 | 1.397600E+02 | -4.770000E-01 | 4.340100E+01 |
| 7.715500E+08 | -2.134900E+01 | 1.324300E+02 | -5.170000E-01 | 2.136700E+01 |
| 8.209000E+08 | -2.095100E+01 | 1.250400E+02 | -5.510000E-01 | -7.072400E-01 |
| 8.702500E+08 | -2.081400E+01 | 1.174200E+02 | -5.860000E-01 | -2.283900E+01 |
| 9.196000E+08 | -2.091600E+01 | 1.100700E+02 | -6.110000E-01 | -4.505600E+01 |
| 9.689500E+08 | -2.122400E+01 | 1.025600E+02 | -6.490000E-01 | -6.739700E+01 |
| 1.018300E+09 | -2.190300E+01 | 9.563300E+01 | -6.710000E-01 | -8.986400E+01 |
| 1.067650E+09 | -2.321200E+01 | 9.183600E+01 | -6.960000E-01 | -1.124600E+02 |
| 1.117000E+09 | -2.364400E+01 | 9.735800E+01 | -7.340000E-01 | -1.351500E+02 |
| 1.166350E+09 | -2.264900E+01 | 1.024100E+02 | -7.680000E-01 | -1.579000E+02 |
| 1.215700E+09 | -2.171200E+01 | 9.598200E+01 | -8.000000E-01 | 1.792200E+02 |
| 1.265050E+09 | -2.138800E+01 | 8.789200E+01 | -8.420000E-01 | 1.562200E+02 |
| 1.314400E+09 | -2.137600E+01 | 8.043900E+01 | -8.660000E-01 | 1.332400E+02 |
| 1.363750E+09 | -2.160700E+01 | 7.287400E+01 | -8.950000E-01 | 1.100700E+02 |
| 1.413100E+09 | -2.216500E+01 | 6.599900E+01 | -9.240000E-01 | 8.681400E+01 |
| 1.462450E+09 | -2.303300E+01 | 5.966300E+01 | -9.570000E-01 | 6.337900E+01 |
| 1.511800E+09 | -2.442400E+01 | 5.856300E+01 | -9.830000E-01 | 3.985200E+01 |
| 1.561150E+09 | -2.496900E+01 | 6.206000E+01 | -1.020000E+00 | 1.625700E+01 |
| 1.610500E+09 | -2.421700E+01 | 6.413300E+01 | -1.054000E+00 | -7.481700E+00 |

| | | | | |
|---|---|---|---|---|
| 1.659850E+09 | -2.394000E+01 | 5.696500E+01 | -1.087000E+00 | -3.128900E+01 |
| 1.709200E+09 | -2.408100E+01 | 4.908700E+01 | -1.128000E+00 | -5.530700E+01 |
| 1.758550E+09 | -2.452400E+01 | 4.009300E+01 | -1.166000E+00 | -7.932700E+01 |
| 1.807900E+09 | -2.505100E+01 | 3.149600E+01 | -1.190000E+00 | -1.034500E+02 |
| 1.857250E+09 | -2.564100E+01 | 2.126000E+01 | -1.242000E+00 | -1.278200E+02 |
| 1.906600E+09 | -2.623000E+01 | 1.099000E+01 | -1.282000E+00 | -1.522000E+02 |
| 1.955950E+09 | -2.647900E+01 | -1.192000E+00 | -1.330000E+00 | -1.767500E+02 |
| 2.005300E+09 | -2.645300E+01 | -1.426200E+01 | -1.366000E+00 | 1.586200E+02 |
| 2.054650E+09 | -2.573300E+01 | -3.235900E+01 | -1.408000E+00 | 1.338400E+02 |
| 2.104000E+09 | -2.603600E+01 | -5.440700E+01 | -1.452000E+00 | 1.089400E+02 |
| 2.153350E+09 | -2.696200E+01 | -7.084900E+01 | -1.496000E+00 | 8.393700E+01 |
| 2.202700E+09 | -2.703500E+01 | -8.330900E+01 | -1.545000E+00 | 5.871000E+01 |
| 2.252050E+09 | -2.664000E+01 | -9.596100E+01 | -1.589000E+00 | 3.341500E+01 |
| 2.301400E+09 | -2.590000E+01 | -1.078500E+02 | -1.653000E+00 | 7.936200E+00 |
| 2.350750E+09 | -2.499000E+01 | -1.200000E+02 | -1.747000E+00 | -1.779000E+01 |
| 2.400100E+09 | -2.394700E+01 | -1.306900E+02 | -1.829000E+00 | -4.363500E+01 |
| 2.449450E+09 | -2.286900E+01 | -1.407800E+02 | -1.970000E+00 | -6.973600E+01 |
| 2.498800E+09 | -2.195400E+01 | -1.476500E+02 | -2.091000E+00 | -9.609500E+01 |
| 2.548150E+09 | -2.084100E+01 | -1.510700E+02 | -2.304000E+00 | -1.227700E+02 |
| 2.597500E+09 | -1.936100E+01 | -1.525200E+02 | -2.579000E+00 | -1.496400E+02 |
| 2.646850E+09 | -1.699100E+01 | -1.543000E+02 | -2.923000E+00 | -1.767300E+02 |
| 2.696200E+09 | -1.427100E+01 | -1.630000E+02 | -3.450000E+00 | 1.560700E+02 |
| 2.745550E+09 | -1.238400E+01 | -1.754500E+02 | -3.913000E+00 | 1.296000E+02 |
| 2.794900E+09 | -1.093300E+01 | 1.725000E+02 | -4.717000E+00 | 1.025800E+02 |
| 2.844250E+09 | -9.742000E+00 | 1.608200E+02 | -5.549000E+00 | 7.779400E+01 |
| 2.893600E+09 | -8.669000E+00 | 1.499400E+02 | -6.259000E+00 | 5.292000E+01 |
| 2.942950E+09 | -7.633000E+00 | 1.393700E+02 | -7.251000E+00 | 2.871400E+01 |
| 2.992300E+09 | -6.525000E+00 | 1.290300E+02 | -8.008000E+00 | 6.579400E+00 |
| 3.041650E+09 | -5.296000E+00 | 1.175000E+02 | -8.838000E+00 | -1.493200E+01 |
| 3.091000E+09 | -4.139000E+00 | 1.033800E+02 | -9.461000E+00 | -3.507200E+01 |
| 3.140350E+09 | -3.348000E+00 | 8.774200E+01 | -1.007000E+01 | -5.445200E+01 |
| 3.189700E+09 | -2.865000E+00 | 7.189700E+01 | -1.040400E+01 | -7.252200E+01 |
| 3.239050E+09 | -2.624000E+00 | 5.605000E+01 | -1.043600E+01 | -9.069800E+01 |
| 3.288400E+09 | -2.593000E+00 | 4.018500E+01 | -1.045600E+01 | -1.082500E+02 |
| 3.337750E+09 | -2.778000E+00 | 2.410300E+01 | -9.990000E+00 | -1.256700E+02 |
| 3.387100E+09 | -3.248000E+00 | 7.711000E+00 | -9.410000E+00 | -1.446800E+02 |
| 3.436450E+09 | -4.122000E+00 | -8.699800E+00 | -8.771000E+00 | -1.640000E+02 |
| 3.485800E+09 | -5.589000E+00 | -2.338200E+01 | -7.875000E+00 | 1.759400E+02 |
| 3.535150E+09 | -7.128000E+00 | -3.345700E+01 | -7.148000E+00 | 1.541800E+02 |
| 3.584500E+09 | -8.475000E+00 | -4.177700E+01 | -6.313000E+00 | 1.322700E+02 |
| 3.633850E+09 | -9.660000E+00 | -4.965000E+01 | -5.591000E+00 | 1.090400E+02 |
| 3.683200E+09 | -1.082900E+01 | -5.792500E+01 | -4.847000E+00 | 8.562300E+01 |
| 3.732550E+09 | -1.206700E+01 | -6.643200E+01 | -4.272000E+00 | 6.141200E+01 |
| 3.781900E+09 | -1.340600E+01 | -7.525500E+01 | -3.795000E+00 | 3.771700E+01 |
| 3.831250E+09 | -1.488800E+01 | -8.428800E+01 | -3.399000E+00 | 1.291900E+01 |
| 3.880600E+09 | -1.657500E+01 | -9.343900E+01 | -3.139000E+00 | -1.108200E+01 |
| 3.929950E+09 | -1.852100E+01 | -1.023500E+02 | -2.943000E+00 | -3.543800E+01 |
| 3.979300E+09 | -2.078900E+01 | -1.111800E+02 | -2.901000E+00 | -5.891400E+01 |

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|---|---|---|---|---|
| 4.028650E+09 | -2.278900E+01 | -1.132000E+02 | -2.827000E+00 | -8.197600E+01 |
| 4.078000E+09 | -2.396700E+01 | -1.188700E+02 | -2.772000E+00 | -1.049900E+02 |
| 4.127350E+09 | -2.492800E+01 | -1.273000E+02 | -2.770000E+00 | -1.279000E+02 |
| 4.176700E+09 | -2.581100E+01 | -1.372700E+02 | -2.769000E+00 | -1.503500E+02 |
| 4.226050E+09 | -2.642300E+01 | -1.470100E+02 | -2.763000E+00 | -1.729700E+02 |
| 4.275400E+09 | -2.674700E+01 | -1.576800E+02 | -2.782000E+00 | 1.645600E+02 |
| 4.324750E+09 | -2.685800E+01 | -1.680900E+02 | -2.812000E+00 | 1.419000E+02 |
| 4.374100E+09 | -2.658800E+01 | -1.782800E+02 | -2.856000E+00 | 1.193100E+02 |
| 4.423450E+09 | -2.601300E+01 | 1.714400E+02 | -2.906000E+00 | 9.668700E+01 |
| 4.472800E+09 | -2.501700E+01 | 1.617000E+02 | -2.950000E+00 | 7.398500E+01 |
| 4.522150E+09 | -2.348300E+01 | 1.523500E+02 | -2.998000E+00 | 5.105800E+01 |
| 4.571500E+09 | -2.189100E+01 | 1.365600E+02 | -3.065000E+00 | 2.804700E+01 |
| 4.620850E+09 | -2.095100E+01 | 1.237400E+02 | -3.135000E+00 | 4.974100E+00 |
| 4.670200E+09 | -2.004000E+01 | 1.134200E+02 | -3.204000E+00 | -1.840500E+01 |
| 4.719550E+09 | -1.909800E+01 | 1.046000E+02 | -3.304000E+00 | -4.187000E+01 |
| 4.768900E+09 | -1.825500E+01 | 9.590500E+01 | -3.384000E+00 | -6.546500E+01 |
| 4.818250E+09 | -1.751600E+01 | 8.827700E+01 | -3.497000E+00 | -8.947400E+01 |
| 4.867600E+09 | -1.687300E+01 | 8.067400E+01 | -3.626000E+00 | -1.133700E+02 |
| 4.916950E+09 | -1.649100E+01 | 7.374700E+01 | -3.722000E+00 | -1.375500E+02 |
| 4.966300E+09 | -1.625700E+01 | 6.848600E+01 | -3.836000E+00 | -1.621700E+02 |
| 5.015650E+09 | -1.601000E+01 | 6.605800E+01 | -3.983000E+00 | 1.729100E+02 |
| 5.065000E+09 | -1.534900E+01 | 6.501600E+01 | -4.150000E+00 | 1.477000E+02 |
| 5.114350E+09 | -1.421400E+01 | 6.259200E+01 | -4.347000E+00 | 1.220600E+02 |
| 5.163700E+09 | -1.305600E+01 | 5.623800E+01 | -4.578000E+00 | 9.603300E+01 |
| 5.213050E+09 | -1.226500E+01 | 4.840400E+01 | -4.850000E+00 | 6.967900E+01 |
| 5.262400E+09 | -1.181400E+01 | 4.062500E+01 | -5.132000E+00 | 4.295200E+01 |
| 5.311750E+09 | -1.162300E+01 | 3.429100E+01 | -5.441000E+00 | 1.559500E+01 |
| 5.361100E+09 | -1.145500E+01 | 3.002800E+01 | -5.811000E+00 | -1.242100E+01 |
| 5.410450E+09 | -1.108800E+01 | 2.714300E+01 | -6.284000E+00 | -4.103800E+01 |
| 5.459800E+09 | -1.048900E+01 | 2.442700E+01 | -6.881000E+00 | -7.006900E+01 |
| 5.509150E+09 | -9.642000E+00 | 2.107700E+01 | -7.577000E+00 | -9.926400E+01 |
| 5.558500E+09 | -8.703000E+00 | 1.508100E+01 | -8.337000E+00 | -1.284500E+02 |
| 5.607850E+09 | -8.008000E+00 | 7.926600E+00 | -9.199000E+00 | -1.584400E+02 |
| 5.657200E+09 | -7.498000E+00 | 8.390800E-01 | -1.026700E+01 | 1.716900E+02 |
| 5.706550E+09 | -7.060000E+00 | -5.652500E+00 | -1.144300E+01 | 1.419300E+02 |
| 5.755900E+09 | -6.582000E+00 | -1.174900E+01 | -1.278700E+01 | 1.121000E+02 |
| 5.805250E+09 | -6.004000E+00 | -1.800400E+01 | -1.438900E+01 | 8.331100E+01 |
| 5.854600E+09 | -5.325000E+00 | -2.527400E+01 | -1.603200E+01 | 5.574300E+01 |
| 5.903950E+09 | -4.703000E+00 | -3.411400E+01 | -1.774300E+01 | 2.903300E+01 |
| 5.953300E+09 | -4.247000E+00 | -4.377500E+01 | -1.949700E+01 | 2.916900E+00 |
| 6.002650E+09 | -3.919000E+00 | -5.369800E+01 | -2.112200E+01 | -2.165800E+01 |
| 6.052000E+09 | -3.666000E+00 | -6.380000E+01 | -2.265100E+01 | -4.595300E+01 |
| 6.101350E+09 | -3.462000E+00 | -7.430100E+01 | -2.407800E+01 | -7.022500E+01 |
| 6.150700E+09 | -3.310000E+00 | -8.540200E+01 | -2.533200E+01 | -9.260000E+01 |
| 6.200050E+09 | -3.231000E+00 | -9.732500E+01 | -2.623500E+01 | -1.153000E+02 |
| 6.249400E+09 | -3.258000E+00 | -1.100800E+02 | -2.685200E+01 | -1.369900E+02 |
| 6.298750E+09 | -3.387000E+00 | -1.235900E+02 | -2.706600E+01 | -1.589200E+02 |
| 6.348100E+09 | -3.618000E+00 | -1.378400E+02 | -2.692700E+01 | 1.783400E+02 |

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|---|---|---|---|---|
| 6.397450E+09 | -3.934000E+00 | -1.529900E+02 | -2.651200E+01 | 1.564100E+02 |
| 6.446800E+09 | -4.330000E+00 | -1.691200E+02 | -2.578500E+01 | 1.331400E+02 |
| 6.496150E+09 | -4.810000E+00 | 1.737800E+02 | -2.472000E+01 | 1.102100E+02 |
| 6.545500E+09 | -5.386000E+00 | 1.557000E+02 | -2.353700E+01 | 8.572800E+01 |
| 6.594850E+09 | -6.048000E+00 | 1.369300E+02 | -2.219600E+01 | 6.128400E+01 |
| 6.644200E+09 | -6.833000E+00 | 1.181300E+02 | -2.069600E+01 | 3.670900E+01 |
| 6.693550E+09 | -7.648000E+00 | 9.986200E+01 | -1.920400E+01 | 1.058700E+01 |
| 6.742900E+09 | -8.406000E+00 | 8.240700E+01 | -1.771600E+01 | -1.550900E+01 |
| 6.792250E+09 | -9.087000E+00 | 6.570400E+01 | -1.636400E+01 | -4.250600E+01 |
| 6.841600E+09 | -9.643000E+00 | 4.986400E+01 | -1.507400E+01 | -6.907800E+01 |
| 6.890950E+09 | -1.008400E+01 | 3.460800E+01 | -1.388300E+01 | -9.615900E+01 |
| 6.940300E+09 | -1.048300E+01 | 2.002100E+01 | -1.286300E+01 | -1.243500E+02 |
| 6.989650E+09 | -1.089000E+01 | 6.620600E+00 | -1.189500E+01 | -1.516800E+02 |
| 7.039000E+09 | -1.130700E+01 | -4.967200E+00 | -1.117300E+01 | -1.797500E+02 |
| 7.088350E+09 | -1.166700E+01 | -1.417400E+01 | -1.046700E+01 | 1.529800E+02 |
| 7.137700E+09 | -1.184100E+01 | -2.117600E+01 | -9.900000E+00 | 1.252200E+02 |
| 7.187050E+09 | -1.172200E+01 | -2.718300E+01 | -9.575000E+00 | 9.778900E+01 |
| 7.236400E+09 | -1.143500E+01 | -3.320500E+01 | -9.160000E+00 | 7.122000E+01 |
| 7.285750E+09 | -1.111200E+01 | -3.955900E+01 | -8.916000E+00 | 4.455800E+01 |
| 7.335100E+09 | -1.083600E+01 | -4.614300E+01 | -8.711000E+00 | 1.895400E+01 |
| 7.384450E+09 | -1.070600E+01 | -5.264800E+01 | -8.513000E+00 | -6.630200E+00 |
| 7.433800E+09 | -1.071600E+01 | -5.817800E+01 | -8.271000E+00 | -3.185500E+01 |
| 7.483150E+09 | -1.071900E+01 | -6.203300E+01 | -8.138000E+00 | -5.754200E+01 |
| 7.532500E+09 | -1.057100E+01 | -6.475100E+01 | -8.112000E+00 | -8.237500E+01 |
| 7.581850E+09 | -1.019100E+01 | -6.748400E+01 | -7.891000E+00 | -1.067100E+02 |
| 7.631200E+09 | -9.676000E+00 | -7.133100E+01 | -7.913000E+00 | -1.324200E+02 |
| 7.680550E+09 | -9.211000E+00 | -7.647200E+01 | -8.026000E+00 | -1.565800E+02 |
| 7.729900E+09 | -8.937000E+00 | -8.223800E+01 | -7.893000E+00 | 1.789900E+02 |
| 7.779250E+09 | -8.853000E+00 | -8.783800E+01 | -8.043000E+00 | 1.545800E+02 |
| 7.828600E+09 | -8.952000E+00 | -9.234100E+01 | -7.991000E+00 | 1.308000E+02 |
| 7.877950E+09 | -9.021000E+00 | -9.506600E+01 | -7.932000E+00 | 1.050500E+02 |
| 7.927300E+09 | -8.875000E+00 | -9.683900E+01 | -8.187000E+00 | 7.928600E+01 |
| 7.976650E+09 | -8.511000E+00 | -9.903400E+01 | -8.355000E+00 | 5.451600E+01 |
| 8.026000E+09 | -8.065000E+00 | -1.024700E+02 | -8.447000E+00 | 2.825000E+01 |
| 8.075350E+09 | -7.687000E+00 | -1.071400E+02 | -8.827000E+00 | 1.777000E+00 |
| 8.124700E+09 | -7.497000E+00 | -1.122200E+02 | -9.318000E+00 | -2.358200E+01 |
| 8.174050E+09 | -7.446000E+00 | -1.167700E+02 | -9.437000E+00 | -4.935200E+01 |
| 8.223400E+09 | -7.429000E+00 | -1.202900E+02 | -9.725000E+00 | -7.746600E+01 |
| 8.272750E+09 | -7.301000E+00 | -1.230900E+02 | -1.045400E+01 | -1.049400E+02 |
| 8.322100E+09 | -7.023000E+00 | -1.258700E+02 | -1.090600E+01 | -1.315800E+02 |
| 8.371450E+09 | -6.586000E+00 | -1.296100E+02 | -1.155700E+01 | -1.605900E+02 |
| 8.420800E+09 | -6.158000E+00 | -1.349300E+02 | -1.242900E+01 | 1.715000E+02 |
| 8.470150E+09 | -5.887000E+00 | -1.412100E+02 | -1.318800E+01 | 1.439600E+02 |
| 8.519500E+09 | -5.750000E+00 | -1.475800E+02 | -1.417000E+01 | 1.152500E+02 |
| 8.568850E+09 | -5.681000E+00 | -1.539500E+02 | -1.531200E+01 | 8.864700E+01 |
| 8.618200E+09 | -5.627000E+00 | -1.603200E+02 | -1.624700E+01 | 5.941000E+01 |
| 8.667550E+09 | -5.545000E+00 | -1.671000E+02 | -1.761800E+01 | 2.919100E+01 |
| 8.716900E+09 | -5.459000E+00 | -1.748500E+02 | -1.926800E+01 | 1.292300E+00 |

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|---|---|---|---|---|
| 8.766250E+09 | -5.443000E+00 | 1.758700E+02 | -2.068700E+01 | -2.750800E+01 |
| 8.815600E+09 | -5.595000E+00 | 1.651100E+02 | -2.225000E+01 | -5.695200E+01 |
| 8.864950E+09 | -5.925000E+00 | 1.528400E+02 | -2.377200E+01 | -8.787600E+01 |
| 8.914300E+09 | -6.401000E+00 | 1.388900E+02 | -2.521000E+01 | -1.183600E+02 |
| 8.963650E+09 | -6.950000E+00 | 1.227700E+02 | -2.646700E+01 | -1.490600E+02 |
| 9.013000E+09 | -7.466000E+00 | 1.044300E+02 | -2.747600E+01 | 1.798700E+02 |
| 9.062350E+09 | -7.882000E+00 | 8.415400E+01 | -2.839400E+01 | 1.486800E+02 |
| 9.111700E+09 | -8.189000E+00 | 6.261200E+01 | -2.924800E+01 | 1.182800E+02 |
| 9.161050E+09 | -8.379000E+00 | 4.029500E+01 | -2.984400E+01 | 9.045600E+01 |
| 9.210400E+09 | -8.475000E+00 | 1.761700E+01 | -3.009600E+01 | 6.189800E+01 |
| 9.259750E+09 | -8.467000E+00 | -5.027600E+00 | -3.026000E+01 | 3.363900E+01 |
| 9.309100E+09 | -8.354000E+00 | -2.732400E+01 | -3.034400E+01 | 7.996700E+00 |
| 9.358450E+09 | -8.123000E+00 | -4.894700E+01 | -3.000500E+01 | -1.601700E+01 |
| 9.407800E+09 | -7.774000E+00 | -6.930300E+01 | -2.953600E+01 | -3.992400E+01 |
| 9.457150E+09 | -7.319000E+00 | -8.793300E+01 | -2.925400E+01 | -6.296800E+01 |
| 9.506500E+09 | -6.814000E+00 | -1.041500E+02 | -2.881800E+01 | -8.457000E+01 |
| 9.555850E+09 | -6.347000E+00 | -1.179200E+02 | -2.835200E+01 | -1.068000E+02 |
| 9.605200E+09 | -5.981000E+00 | -1.294100E+02 | -2.785500E+01 | -1.300800E+02 |
| 9.654550E+09 | -5.723000E+00 | -1.392000E+02 | -2.731900E+01 | -1.552000E+02 |
| 9.703900E+09 | -5.583000E+00 | -1.476300E+02 | -2.687500E+01 | 1.791200E+02 |
| 9.753250E+09 | -5.529000E+00 | -1.550400E+02 | -2.621300E+01 | 1.528200E+02 |
| 9.802600E+09 | -5.533000E+00 | -1.612400E+02 | -2.560400E+01 | 1.276900E+02 |
| 9.851950E+09 | -5.574000E+00 | -1.663700E+02 | -2.503900E+01 | 1.044300E+02 |
| 9.901300E+09 | -5.640000E+00 | -1.705000E+02 | -2.449200E+01 | 8.203400E+01 |
| 9.950650E+09 | -5.710000E+00 | -1.738100E+02 | -2.423300E+01 | 6.228000E+01 |
| 1.000000E+10 | -5.775000E+00 | -1.763600E+02 | -2.379600E+01 | 4.580500E+01 |

## A.7. 104-mil wide N-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -4.538867E+01 | 1.787031E+02 | -5.764771E-02 | -3.463867E+01 |
| 1.793500E+08 | -4.423828E+01 | 1.757500E+02 | -6.439972E-02 | -3.941406E+01 |
| 2.287000E+08 | -4.282031E+01 | 1.721953E+02 | -6.858063E-02 | -4.497460E+01 |
| 2.780500E+08 | -4.131055E+01 | 1.682266E+02 | -7.413864E-02 | -5.131054E+01 |
| 3.274000E+08 | -3.958789E+01 | 1.633594E+02 | -8.346176E-02 | -5.846680E+01 |
| 3.767500E+08 | -3.768945E+01 | 1.577812E+02 | -9.232712E-02 | -6.642187E+01 |
| 4.261000E+08 | -3.566601E+01 | 1.514453E+02 | -1.052361E-01 | -7.517187E+01 |
| 4.754500E+08 | -3.385547E+01 | 1.457344E+02 | -1.196594E-01 | -8.391016E+01 |
| 5.248000E+08 | -3.221094E+01 | 1.391953E+02 | -1.398697E-01 | -9.266405E+01 |
| 5.741500E+08 | -3.041308E+01 | 1.324687E+02 | -1.555786E-01 | -1.014570E+02 |
| 6.235000E+08 | -2.870800E+01 | 1.251445E+02 | -1.722565E-01 | -1.102578E+02 |
| 6.728500E+08 | -2.708887E+01 | 1.168984E+02 | -1.867676E-01 | -1.190781E+02 |
| 7.222000E+08 | -2.566015E+01 | 1.082734E+02 | -2.024307E-01 | -1.279140E+02 |
| 7.715500E+08 | -2.445215E+01 | 9.939453E+01 | -2.237015E-01 | -1.367812E+02 |
| 8.209000E+08 | -2.329590E+01 | 9.003124E+01 | -2.431335E-01 | -1.457031E+02 |
| 8.702500E+08 | -2.234179E+01 | 8.069139E+01 | -2.631683E-01 | -1.546562E+02 |
| 9.196000E+08 | -2.155566E+01 | 7.117969E+01 | -2.854919E-01 | -1.636250E+02 |

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|---|---|---|---|---|
| 9.689500E+08 | -2.091015E+01 | 6.174805E+01 | -2.984314E-01 | -1.726875E+02 |
| 1.018300E+09 | -2.044434E+01 | 5.231054E+01 | -3.134613E-01 | 1.782578E+02 |
| 1.067650E+09 | -2.010352E+01 | 4.285352E+01 | -3.285675E-01 | 1.691484E+02 |
| 1.117000E+09 | -1.993262E+01 | 3.356836E+01 | -3.430328E-01 | 1.600000E+02 |
| 1.166350E+09 | -1.993652E+01 | 2.426855E+01 | -3.639374E-01 | 1.508047E+02 |
| 1.215700E+09 | -2.013184E+01 | 1.534375E+01 | -3.824921E-01 | 1.415390E+02 |
| 1.265050E+09 | -2.058203E+01 | 6.554688E+00 | -4.045868E-01 | 1.322187E+02 |
| 1.314400E+09 | -2.123242E+01 | -1.779785E+00 | -4.153442E-01 | 1.228008E+02 |
| 1.363750E+09 | -2.218945E+01 | -8.419922E+00 | -4.291229E-01 | 1.133594E+02 |
| 1.413100E+09 | -2.356934E+01 | -1.185449E+01 | -4.394073E-01 | 1.038320E+02 |
| 1.462450E+09 | -2.458887E+01 | -1.160303E+01 | -4.523163E-01 | 9.427343E+01 |
| 1.511800E+09 | -2.525683E+01 | -9.708008E+00 | -4.689026E-01 | 8.466015E+01 |
| 1.561150E+09 | -2.564258E+01 | -7.104248E+00 | -4.880981E-01 | 7.492578E+01 |
| 1.610500E+09 | -2.579785E+01 | -4.365723E+00 | -5.101624E-01 | 6.517187E+01 |
| 1.659850E+09 | -2.572363E+01 | -1.505127E+00 | -5.398865E-01 | 5.532812E+01 |
| 1.709200E+09 | -2.543457E+01 | 1.443298E+00 | -5.704651E-01 | 4.541992E+01 |
| 1.758550E+09 | -2.492383E+01 | 3.869873E+00 | -6.021729E-01 | 3.544726E+01 |
| 1.807900E+09 | -2.408984E+01 | 5.925537E+00 | -6.304016E-01 | 2.548828E+01 |
| 1.857250E+09 | -2.300976E+01 | 7.389648E+00 | -6.849670E-01 | 1.543701E+01 |
| 1.906600E+09 | -2.162304E+01 | 6.847168E+00 | -7.391663E-01 | 5.329590E+00 |
| 1.955950E+09 | -1.976074E+01 | 2.860474E+00 | -8.035278E-01 | -4.632324E+00 |
| 2.005300E+09 | -1.824707E+01 | -5.029053E+00 | -8.682556E-01 | -1.467090E+01 |
| 2.054650E+09 | -1.701660E+01 | -1.486621E+01 | -9.441223E-01 | -2.469336E+01 |
| 2.104000E+09 | -1.606738E+01 | -2.579492E+01 | -1.007507E+00 | -3.457617E+01 |
| 2.153350E+09 | -1.530273E+01 | -3.671679E+01 | -1.048462E+00 | -4.445508E+01 |
| 2.202700E+09 | -1.462354E+01 | -4.799805E+01 | -1.101379E+00 | -5.438867E+01 |
| 2.252050E+09 | -1.405420E+01 | -5.946484E+01 | -1.133972E+00 | -6.439453E+01 |
| 2.301400E+09 | -1.356055E+01 | -7.119141E+01 | -1.175354E+00 | -7.430859E+01 |
| 2.350750E+09 | -1.315527E+01 | -8.292187E+01 | -1.218079E+00 | -8.428905E+01 |
| 2.400100E+09 | -1.282227E+01 | -9.466797E+01 | -1.243286E+00 | -9.419531E+01 |
| 2.449450E+09 | -1.251025E+01 | -1.063242E+02 | -1.265320E+00 | -1.040703E+02 |
| 2.498800E+09 | -1.223682E+01 | -1.178594E+02 | -1.289917E+00 | -1.140820E+02 |
| 2.548150E+09 | -1.195410E+01 | -1.293750E+02 | -1.301880E+00 | -1.240703E+02 |
| 2.597500E+09 | -1.169580E+01 | -1.409609E+02 | -1.327393E+00 | -1.340937E+02 |
| 2.646850E+09 | -1.138184E+01 | -1.522969E+02 | -1.337463E+00 | -1.442188E+02 |
| 2.696200E+09 | -1.106787E+01 | -1.639609E+02 | -1.396240E+00 | -1.542031E+02 |
| 2.745550E+09 | -1.079395E+01 | -1.756406E+02 | -1.440552E+00 | -1.643125E+02 |
| 2.794900E+09 | -1.051465E+01 | 1.727890E+02 | -1.492310E+00 | -1.740234E+02 |
| 2.844250E+09 | -1.023975E+01 | 1.615391E+02 | -1.559570E+00 | 1.760781E+02 |
| 2.893600E+09 | -9.945801E+00 | 1.502969E+02 | -1.624695E+00 | 1.663594E+02 |
| 2.942950E+09 | -9.649902E+00 | 1.391797E+02 | -1.702942E+00 | 1.566328E+02 |
| 2.992300E+09 | -9.345215E+00 | 1.281172E+02 | -1.776611E+00 | 1.470391E+02 |
| 3.041650E+09 | -9.035645E+00 | 1.171094E+02 | -1.863892E+00 | 1.376172E+02 |
| 3.091000E+09 | -8.748047E+00 | 1.063320E+02 | -1.976563E+00 | 1.283125E+02 |
| 3.140350E+09 | -8.470703E+00 | 9.562891E+01 | -2.039673E+00 | 1.190039E+02 |
| 3.189700E+09 | -8.208496E+00 | 8.519531E+01 | -2.127563E+00 | 1.101523E+02 |
| 3.239050E+09 | -7.961182E+00 | 7.484375E+01 | -2.215088E+00 | 1.010703E+02 |
| 3.288400E+09 | -7.718506E+00 | 6.471093E+01 | -2.266602E+00 | 9.235155E+01 |
| 3.337750E+09 | -7.509766E+00 | 5.465820E+01 | -2.329712E+00 | 8.348047E+01 |

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|---|---|---|---|---|
| 3.387100E+09 | -7.327637E+00 | 4.468946E+01 | -2.363892E+00 | 7.503124E+01 |
| 3.436450E+09 | -7.180664E+00 | 3.491796E+01 | -2.428101E+00 | 6.640234E+01 |
| 3.485800E+09 | -7.048584E+00 | 2.516602E+01 | -2.418091E+00 | 5.791406E+01 |
| 3.535150E+09 | -6.954590E+00 | 1.560986E+01 | -2.433472E+00 | 4.957421E+01 |
| 3.584500E+09 | -6.898926E+00 | 6.168701E+00 | -2.432983E+00 | 4.102735E+01 |
| 3.633850E+09 | -6.876953E+00 | -3.364624E+00 | -2.403809E+00 | 3.250000E+01 |
| 3.683200E+09 | -6.893555E+00 | -1.250684E+01 | -2.383545E+00 | 2.434961E+01 |
| 3.732550E+09 | -6.915527E+00 | -2.178125E+01 | -2.377563E+00 | 1.583252E+01 |
| 3.781900E+09 | -6.956543E+00 | -3.093652E+01 | -2.319580E+00 | 7.323730E+00 |
| 3.831250E+09 | -7.041504E+00 | -4.028320E+01 | -2.276611E+00 | -1.036865E+00 |
| 3.880600E+09 | -7.147217E+00 | -4.973242E+01 | -2.233643E+00 | -9.485352E+00 |
| 3.929950E+09 | -7.296875E+00 | -5.916797E+01 | -2.194702E+00 | -1.821191E+01 |
| 3.979300E+09 | -7.479004E+00 | -6.881249E+01 | -2.102417E+00 | -2.679980E+01 |
| 4.028650E+09 | -7.703125E+00 | -7.846484E+01 | -2.078003E+00 | -3.533398E+01 |
| 4.078000E+09 | -7.966797E+00 | -8.818750E+01 | -2.050293E+00 | -4.406054E+01 |
| 4.127350E+09 | -8.251465E+00 | -9.809374E+01 | -1.990784E+00 | -5.273438E+01 |
| 4.176700E+09 | -8.563965E+00 | -1.079961E+02 | -1.931885E+00 | -6.135351E+01 |
| 4.226050E+09 | -8.902344E+00 | -1.183906E+02 | -1.901245E+00 | -7.021874E+01 |
| 4.275400E+09 | -9.286621E+00 | -1.287656E+02 | -1.850525E+00 | -7.913671E+01 |
| 4.324750E+09 | -9.731445E+00 | -1.393594E+02 | -1.807617E+00 | -8.796484E+01 |
| 4.374100E+09 | -1.019482E+01 | -1.500547E+02 | -1.782410E+00 | -9.699219E+01 |
| 4.423450E+09 | -1.068750E+01 | -1.608281E+02 | -1.755127E+00 | -1.060469E+02 |
| 4.472800E+09 | -1.119531E+01 | -1.718281E+02 | -1.724487E+00 | -1.151250E+02 |
| 4.522150E+09 | -1.173682E+01 | 1.771875E+02 | -1.712708E+00 | -1.242891E+02 |
| 4.571500E+09 | -1.228711E+01 | 1.660391E+02 | -1.694641E+00 | -1.335625E+02 |
| 4.620850E+09 | -1.283643E+01 | 1.548984E+02 | -1.667480E+00 | -1.429531E+02 |
| 4.670200E+09 | -1.343066E+01 | 1.435469E+02 | -1.662842E+00 | -1.523672E+02 |
| 4.719550E+09 | -1.400928E+01 | 1.323047E+02 | -1.673523E+00 | -1.619531E+02 |
| 4.768900E+09 | -1.460840E+01 | 1.214141E+02 | -1.687378E+00 | -1.716250E+02 |
| 4.818250E+09 | -1.521777E+01 | 1.104766E+02 | -1.708740E+00 | 1.785938E+02 |
| 4.867600E+09 | -1.583447E+01 | 1.000469E+02 | -1.742126E+00 | 1.687969E+02 |
| 4.916950E+09 | -1.654004E+01 | 8.993359E+01 | -1.787415E+00 | 1.588047E+02 |
| 4.966300E+09 | -1.723145E+01 | 8.057032E+01 | -1.835693E+00 | 1.487422E+02 |
| 5.015650E+09 | -1.796387E+01 | 7.325390E+01 | -1.895996E+00 | 1.385937E+02 |
| 5.065000E+09 | -1.866406E+01 | 6.762890E+01 | -1.974121E+00 | 1.282891E+02 |
| 5.114350E+09 | -1.915918E+01 | 6.343359E+01 | -2.062866E+00 | 1.178125E+02 |
| 5.163700E+09 | -1.941992E+01 | 6.064062E+01 | -2.168945E+00 | 1.072461E+02 |
| 5.213050E+09 | -1.943262E+01 | 5.890038E+01 | -2.284668E+00 | 9.656639E+01 |
| 5.262400E+09 | -1.921679E+01 | 5.769140E+01 | -2.418213E+00 | 8.573046E+01 |
| 5.311750E+09 | -1.877637E+01 | 5.656445E+01 | -2.568115E+00 | 7.472656E+01 |
| 5.361100E+09 | -1.813086E+01 | 5.566211E+01 | -2.745117E+00 | 6.365234E+01 |
| 5.410450E+09 | -1.728808E+01 | 5.436718E+01 | -2.939697E+00 | 5.258594E+01 |
| 5.459800E+09 | -1.621387E+01 | 5.304882E+01 | -3.161865E+00 | 4.144727E+01 |
| 5.509150E+09 | -1.501367E+01 | 5.111523E+01 | -3.394409E+00 | 3.013769E+01 |
| 5.558500E+09 | -1.363672E+01 | 4.727539E+01 | -3.653687E+00 | 1.887402E+01 |
| 5.607850E+09 | -1.215186E+01 | 4.194336E+01 | -3.943359E+00 | 7.640869E+00 |
| 5.657200E+09 | -1.078174E+01 | 3.528515E+01 | -4.257080E+00 | -3.466187E+00 |
| 5.706550E+09 | -9.556152E+00 | 2.721094E+01 | -4.550537E+00 | -1.443066E+01 |
| 5.755900E+09 | -8.465332E+00 | 1.850976E+01 | -4.837158E+00 | -2.528711E+01 |

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|---|---|---|---|---|
| 5.805250E+09 | -7.530762E+00 | 9.235352E+00 | -5.146729E+00 | -3.606836E+01 |
| 5.854600E+09 | -6.727295E+00 | -2.485657E-01 | -5.434326E+00 | -4.686328E+01 |
| 5.903950E+09 | -6.061035E+00 | -9.827637E+00 | -5.691650E+00 | -5.741796E+01 |
| 5.953300E+09 | -5.495117E+00 | -1.936426E+01 | -5.962158E+00 | -6.789844E+01 |
| 6.002650E+09 | -5.019531E+00 | -2.885742E+01 | -6.197510E+00 | -7.830859E+01 |
| 6.052000E+09 | -4.626709E+00 | -3.834570E+01 | -6.406494E+00 | -8.844530E+01 |
| 6.101350E+09 | -4.308105E+00 | -4.773438E+01 | -6.598633E+00 | -9.842577E+01 |
| 6.150700E+09 | -4.069824E+00 | -5.706055E+01 | -6.733398E+00 | -1.082930E+02 |
| 6.200050E+09 | -3.880371E+00 | -6.630077E+01 | -6.851563E+00 | -1.181758E+02 |
| 6.249400E+09 | -3.736206E+00 | -7.539063E+01 | -6.928711E+00 | -1.280859E+02 |
| 6.298750E+09 | -3.635986E+00 | -8.459375E+01 | -7.014648E+00 | -1.376562E+02 |
| 6.348100E+09 | -3.578857E+00 | -9.376953E+01 | -7.041748E+00 | -1.474219E+02 |
| 6.397450E+09 | -3.572510E+00 | -1.029688E+02 | -7.023926E+00 | -1.567422E+02 |
| 6.446800E+09 | -3.598267E+00 | -1.123203E+02 | -6.991455E+00 | -1.661719E+02 |
| 6.496150E+09 | -3.667114E+00 | -1.216875E+02 | -6.929688E+00 | -1.756250E+02 |
| 6.545500E+09 | -3.777100E+00 | -1.313281E+02 | -6.839111E+00 | 1.749141E+02 |
| 6.594850E+09 | -3.911011E+00 | -1.410312E+02 | -6.730225E+00 | 1.656484E+02 |
| 6.644200E+09 | -4.097412E+00 | -1.510156E+02 | -6.586914E+00 | 1.561797E+02 |
| 6.693550E+09 | -4.306396E+00 | -1.612813E+02 | -6.444824E+00 | 1.467031E+02 |
| 6.742900E+09 | -4.560303E+00 | -1.717578E+02 | -6.248047E+00 | 1.372031E+02 |
| 6.792250E+09 | -4.851318E+00 | 1.773438E+02 | -6.083984E+00 | 1.278086E+02 |
| 6.841600E+09 | -5.168945E+00 | 1.662109E+02 | -5.878662E+00 | 1.179844E+02 |
| 6.890950E+09 | -5.526611E+00 | 1.546875E+02 | -5.669434E+00 | 1.085625E+02 |
| 6.940300E+09 | -5.878418E+00 | 1.427187E+02 | -5.497314E+00 | 9.870703E+01 |
| 6.989650E+09 | -6.240234E+00 | 1.305078E+02 | -5.310547E+00 | 8.887110E+01 |
| 7.039000E+09 | -6.587402E+00 | 1.178437E+02 | -5.106445E+00 | 7.896484E+01 |
| 7.088350E+09 | -6.908203E+00 | 1.050078E+02 | -4.916504E+00 | 6.907812E+01 |
| 7.137700E+09 | -7.199463E+00 | 9.181641E+01 | -4.769775E+00 | 5.887109E+01 |
| 7.187050E+09 | -7.423096E+00 | 7.855078E+01 | -4.621094E+00 | 4.861133E+01 |
| 7.236400E+09 | -7.602051E+00 | 6.521874E+01 | -4.452637E+00 | 3.844336E+01 |
| 7.285750E+09 | -7.696533E+00 | 5.185741E+01 | -4.396729E+00 | 2.836719E+01 |
| 7.335100E+09 | -7.729736E+00 | 3.871484E+01 | -4.329102E+00 | 1.763574E+01 |
| 7.384450E+09 | -7.697266E+00 | 2.562012E+01 | -4.255371E+00 | 7.476074E+00 |
| 7.433800E+09 | -7.589355E+00 | 1.282617E+01 | -4.277588E+00 | -2.798828E+00 |
| 7.483150E+09 | -7.455078E+00 | 3.941345E-01 | -4.294922E+00 | -1.318799E+01 |
| 7.532500E+09 | -7.268555E+00 | -1.165137E+01 | -4.324951E+00 | -2.357715E+01 |
| 7.581850E+09 | -7.067871E+00 | -2.321191E+01 | -4.396240E+00 | -3.351563E+01 |
| 7.631200E+09 | -6.851318E+00 | -3.448047E+01 | -4.526611E+00 | -4.339063E+01 |
| 7.680550E+09 | -6.636719E+00 | -4.509766E+01 | -4.642822E+00 | -5.327734E+01 |
| 7.729900E+09 | -6.463623E+00 | -5.535546E+01 | -4.734863E+00 | -6.283789E+01 |
| 7.779250E+09 | -6.315918E+00 | -6.523828E+01 | -4.927246E+00 | -7.208984E+01 |
| 7.828600E+09 | -6.233154E+00 | -7.467187E+01 | -5.038086E+00 | -8.194921E+01 |
| 7.877950E+09 | -6.205566E+00 | -8.382030E+01 | -5.107666E+00 | -9.068359E+01 |
| 7.927300E+09 | -6.254395E+00 | -9.240234E+01 | -5.255371E+00 | -1.001523E+02 |
| 7.976650E+09 | -6.402344E+00 | -1.005664E+02 | -5.299561E+00 | -1.094687E+02 |
| 8.026000E+09 | -6.614258E+00 | -1.081250E+02 | -5.342529E+00 | -1.186133E+02 |
| 8.075350E+09 | -6.958008E+00 | -1.148906E+02 | -5.400879E+00 | -1.278633E+02 |
| 8.124700E+09 | -7.375732E+00 | -1.207461E+02 | -5.427734E+00 | -1.377969E+02 |
| 8.174050E+09 | -7.823975E+00 | -1.251367E+02 | -5.437012E+00 | -1.477890E+02 |

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|---|---|---|---|---|
| 8.223400E+09 | -8.266602E+00 | -1.284453E+02 | -5.427490E+00 | -1.579922E+02 |
| 8.272750E+09 | -8.580566E+00 | -1.305391E+02 | -5.523193E+00 | -1.684609E+02 |
| 8.322100E+09 | -8.811523E+00 | -1.317266E+02 | -5.546631E+00 | -1.796953E+02 |
| 8.371450E+09 | -8.901855E+00 | -1.328047E+02 | -5.670654E+00 | 1.696016E+02 |
| 8.420800E+09 | -8.850586E+00 | -1.335625E+02 | -5.818848E+00 | 1.579766E+02 |
| 8.470150E+09 | -8.688477E+00 | -1.342656E+02 | -6.034424E+00 | 1.469609E+02 |
| 8.519500E+09 | -8.407227E+00 | -1.351641E+02 | -6.296631E+00 | 1.353516E+02 |
| 8.568850E+09 | -8.024902E+00 | -1.363437E+02 | -6.607178E+00 | 1.238515E+02 |
| 8.618200E+09 | -7.514404E+00 | -1.381875E+02 | -6.928711E+00 | 1.128398E+02 |
| 8.667550E+09 | -6.899170E+00 | -1.407578E+02 | -7.375488E+00 | 1.018594E+02 |
| 8.716900E+09 | -6.270020E+00 | -1.445234E+02 | -7.697510E+00 | 9.082811E+01 |
| 8.766250E+09 | -5.642090E+00 | -1.495859E+02 | -8.132324E+00 | 8.041016E+01 |
| 8.815600E+09 | -5.122314E+00 | -1.556875E+02 | -8.466309E+00 | 7.005468E+01 |
| 8.864950E+09 | -4.690186E+00 | -1.627187E+02 | -8.843750E+00 | 5.985352E+01 |
| 8.914300E+09 | -4.379639E+00 | -1.699766E+02 | -9.062500E+00 | 4.979101E+01 |
| 8.963650E+09 | -4.210449E+00 | -1.776406E+02 | -9.364746E+00 | 3.997461E+01 |
| 9.013000E+09 | -4.132813E+00 | 1.742734E+02 | -9.486816E+00 | 2.952637E+01 |
| 9.062350E+09 | -4.155273E+00 | 1.661250E+02 | -9.610352E+00 | 1.951269E+01 |
| 9.111700E+09 | -4.284180E+00 | 1.574375E+02 | -9.644043E+00 | 9.290039E+00 |
| 9.161050E+09 | -4.483643E+00 | 1.484375E+02 | -9.676270E+00 | -1.667175E+00 |
| 9.210400E+09 | -4.825928E+00 | 1.389531E+02 | -9.523926E+00 | -1.265234E+01 |
| 9.259750E+09 | -5.268555E+00 | 1.287344E+02 | -9.469727E+00 | -2.377246E+01 |
| 9.309100E+09 | -5.849609E+00 | 1.178672E+02 | -9.271973E+00 | -3.563281E+01 |
| 9.358450E+09 | -6.519775E+00 | 1.056562E+02 | -9.118652E+00 | -4.783203E+01 |
| 9.407800E+09 | -7.275879E+00 | 9.240234E+01 | -8.890137E+00 | -6.033984E+01 |
| 9.457150E+09 | -8.081543E+00 | 7.700390E+01 | -8.729980E+00 | -7.325000E+01 |
| 9.506500E+09 | -8.749512E+00 | 6.019140E+01 | -8.521484E+00 | -8.656641E+01 |
| 9.555850E+09 | -9.302246E+00 | 4.218359E+01 | -8.389160E+00 | -9.986328E+01 |
| 9.605200E+09 | -9.674316E+00 | 2.323144E+01 | -8.254395E+00 | -1.136133E+02 |
| 9.654550E+09 | -9.881348E+00 | 4.031982E+00 | -8.187988E+00 | -1.273281E+02 |
| 9.703900E+09 | -9.931641E+00 | -1.533154E+01 | -8.150391E+00 | -1.410234E+02 |
| 9.753250E+09 | -9.805664E+00 | -3.453125E+01 | -8.207520E+00 | -1.545547E+02 |
| 9.802600E+09 | -9.574219E+00 | -5.232812E+01 | -8.261719E+00 | -1.669297E+02 |
| 9.851950E+09 | -9.215820E+00 | -6.862890E+01 | -8.363281E+00 | -1.779766E+02 |
| 9.901300E+09 | -8.769043E+00 | -8.296875E+01 | -8.459473E+00 | 1.722500E+02 |
| 9.950650E+09 | -8.225098E+00 | -9.547266E+01 | -8.587891E+00 | 1.638672E+02 |
| 1.000000E+10 | -7.623047E+00 | -1.050703E+02 | -8.710449E+00 | 1.566719E+02 |

## A.8. 104-mil wide M-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -3.781641E+01 | -1.597500E+02 | -8.006287E-02 | -4.332617E+01 |
| 1.793500E+08 | -3.691601E+01 | -1.653750E+02 | -9.223557E-02 | -4.926562E+01 |
| 2.287000E+08 | -3.588672E+01 | -1.714453E+02 | -1.055565E-01 | -5.620898E+01 |
| 2.780500E+08 | -3.469141E+01 | -1.788984E+02 | -1.183739E-01 | -6.414063E+01 |
| 3.274000E+08 | -3.339258E+01 | 1.727344E+02 | -1.364288E-01 | -7.307812E+01 |
| 3.767500E+08 | -3.194531E+01 | 1.629609E+02 | -1.565475E-01 | -8.302734E+01 |
| 4.261000E+08 | -3.044238E+01 | 1.523750E+02 | -1.779022E-01 | -9.398438E+01 |

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|---|---|---|---|---|
| 4.754500E+08 | -2.859375E+01 | 1.408672E+02 | -1.999512E-01 | -1.050000E+02 |
| 5.248000E+08 | -2.726855E+01 | 1.305703E+02 | -2.206650E-01 | -1.160234E+02 |
| 5.741500E+08 | -2.581640E+01 | 1.184453E+02 | -2.427597E-01 | -1.270703E+02 |
| 6.235000E+08 | -2.470410E+01 | 1.073125E+02 | -2.620544E-01 | -1.381484E+02 |
| 6.728500E+08 | -2.363574E+01 | 9.484766E+01 | -2.858124E-01 | -1.493125E+02 |
| 7.222000E+08 | -2.284668E+01 | 8.324999E+01 | -3.028412E-01 | -1.604766E+02 |
| 7.715500E+08 | -2.226074E+01 | 7.067577E+01 | -3.226471E-01 | -1.716719E+02 |
| 8.209000E+08 | -2.189941E+01 | 5.875390E+01 | -3.358307E-01 | 1.770781E+02 |
| 8.702500E+08 | -2.182324E+01 | 4.652734E+01 | -3.555298E-01 | 1.657812E+02 |
| 9.196000E+08 | -2.209668E+01 | 3.501172E+01 | -3.727570E-01 | 1.544453E+02 |
| 9.689500E+08 | -2.284472E+01 | 2.383008E+01 | -3.921356E-01 | 1.430234E+02 |
| 1.018300E+09 | -2.430371E+01 | 1.714258E+01 | -4.092255E-01 | 1.316094E+02 |
| 1.067650E+09 | -2.550586E+01 | 1.734179E+01 | -4.253082E-01 | 1.201094E+02 |
| 1.117000E+09 | -2.608203E+01 | 1.890039E+01 | -4.424896E-01 | 1.085547E+02 |
| 1.166350E+09 | -2.637109E+01 | 2.124609E+01 | -4.569092E-01 | 9.691406E+01 |
| 1.215700E+09 | -2.646484E+01 | 2.356836E+01 | -4.777679E-01 | 8.522264E+01 |
| 1.265050E+09 | -2.631348E+01 | 2.589844E+01 | -4.955902E-01 | 7.343750E+01 |
| 1.314400E+09 | -2.598926E+01 | 2.836523E+01 | -5.146179E-01 | 6.164648E+01 |
| 1.363750E+09 | -2.550293E+01 | 3.055273E+01 | -5.458984E-01 | 4.978125E+01 |
| 1.413100E+09 | -2.478906E+01 | 3.262304E+01 | -5.703735E-01 | 3.783789E+01 |
| 1.462450E+09 | -2.380957E+01 | 3.434375E+01 | -5.963745E-01 | 2.589550E+01 |
| 1.511800E+09 | -2.242480E+01 | 3.529492E+01 | -6.254578E-01 | 1.389893E+01 |
| 1.561150E+09 | -2.042773E+01 | 3.190527E+01 | -6.564941E-01 | 1.814087E+00 |
| 1.610500E+09 | -1.877148E+01 | 2.125391E+01 | -6.828613E-01 | -1.027539E+01 |
| 1.659850E+09 | -1.784375E+01 | 9.413574E+00 | -7.105103E-01 | -2.241504E+01 |
| 1.709200E+09 | -1.731348E+01 | -3.495117E+00 | -7.409363E-01 | -3.460742E+01 |
| 1.758550E+09 | -1.712500E+01 | -1.611719E+01 | -7.651367E-01 | -4.690430E+01 |
| 1.807900E+09 | -1.733496E+01 | -2.930957E+01 | -7.886047E-01 | -5.924414E+01 |
| 1.857250E+09 | -1.787890E+01 | -4.159765E+01 | -8.126221E-01 | -7.169922E+01 |
| 1.906600E+09 | -1.917480E+01 | -5.233203E+01 | -8.297119E-01 | -8.424999E+01 |
| 1.955950E+09 | -2.074805E+01 | -5.751953E+01 | -8.508301E-01 | -9.689062E+01 |
| 2.005300E+09 | -2.172754E+01 | -5.895898E+01 | -8.732605E-01 | -1.096992E+02 |
| 2.054650E+09 | -2.230273E+01 | -5.946679E+01 | -9.003601E-01 | -1.225820E+02 |
| 2.104000E+09 | -2.257813E+01 | -5.949219E+01 | -9.301758E-01 | -1.355703E+02 |
| 2.153350E+09 | -2.265625E+01 | -5.970117E+01 | -9.768372E-01 | -1.486406E+02 |
| 2.202700E+09 | -2.258887E+01 | -5.992969E+01 | -1.040100E+00 | -1.617188E+02 |
| 2.252050E+09 | -2.228613E+01 | -5.974609E+01 | -1.078857E+00 | -1.748672E+02 |
| 2.301400E+09 | -2.173047E+01 | -5.987305E+01 | -1.131104E+00 | 1.720000E+02 |
| 2.350750E+09 | -2.088477E+01 | -5.981445E+01 | -1.196594E+00 | 1.588047E+02 |
| 2.400100E+09 | -1.973242E+01 | -6.076562E+01 | -1.262695E+00 | 1.455703E+02 |
| 2.449450E+09 | -1.784863E+01 | -6.356640E+01 | -1.342712E+00 | 1.323828E+02 |
| 2.498800E+09 | -1.567432E+01 | -7.182031E+01 | -1.434387E+00 | 1.191953E+02 |
| 2.548150E+09 | -1.411572E+01 | -8.408983E+01 | -1.514648E+00 | 1.061016E+02 |
| 2.597500E+09 | -1.288281E+01 | -9.732811E+01 | -1.616150E+00 | 9.293360E+01 |
| 2.646850E+09 | -1.191748E+01 | -1.109297E+02 | -1.690735E+00 | 7.989452E+01 |
| 2.696200E+09 | -1.107080E+01 | -1.245313E+02 | -1.811035E+00 | 6.697656E+01 |
| 2.745550E+09 | -1.026563E+01 | -1.380938E+02 | -1.898132E+00 | 5.378515E+01 |
| 2.794900E+09 | -9.560059E+00 | -1.521328E+02 | -2.033325E+00 | 4.105078E+01 |
| 2.844250E+09 | -8.936523E+00 | -1.657969E+02 | -2.178589E+00 | 2.815234E+01 |

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|---|---|---|---|---|
| 2.893600E+09 | -8.386230E+00 | -1.796016E+02 | -2.329224E+00 | 1.553467E+01 |
| 2.942950E+09 | -7.870117E+00 | 1.668672E+02 | -2.500610E+00 | 2.936035E+00 |
| 2.992300E+09 | -7.405273E+00 | 1.534765E+02 | -2.659668E+00 | -9.405762E+00 |
| 3.041650E+09 | -6.974365E+00 | 1.401641E+02 | -2.843384E+00 | -2.144433E+01 |
| 3.091000E+09 | -6.565918E+00 | 1.270351E+02 | -3.059082E+00 | -3.333008E+01 |
| 3.140350E+09 | -6.205322E+00 | 1.141055E+02 | -3.211548E+00 | -4.508398E+01 |
| 3.189700E+09 | -5.874268E+00 | 1.013242E+02 | -3.396118E+00 | -5.625977E+01 |
| 3.239050E+09 | -5.569580E+00 | 8.880468E+01 | -3.584961E+00 | -6.755859E+01 |
| 3.288400E+09 | -5.295654E+00 | 7.644140E+01 | -3.738647E+00 | -7.834765E+01 |
| 3.337750E+09 | -5.056396E+00 | 6.436328E+01 | -3.875000E+00 | -8.926952E+01 |
| 3.387100E+09 | -4.861328E+00 | 5.226563E+01 | -3.967651E+00 | -9.953905E+01 |
| 3.436450E+09 | -4.686035E+00 | 4.041406E+01 | -4.094482E+00 | -1.099492E+02 |
| 3.485800E+09 | -4.557861E+00 | 2.859863E+01 | -4.112061E+00 | -1.201641E+02 |
| 3.535150E+09 | -4.467773E+00 | 1.697168E+01 | -4.142090E+00 | -1.301797E+02 |
| 3.584500E+09 | -4.419434E+00 | 5.538330E+00 | -4.137939E+00 | -1.403984E+02 |
| 3.633850E+09 | -4.408936E+00 | -5.869629E+00 | -4.076172E+00 | -1.506406E+02 |
| 3.683200E+09 | -4.437256E+00 | -1.722852E+01 | -4.017334E+00 | -1.606094E+02 |
| 3.732550E+09 | -4.509033E+00 | -2.865820E+01 | -3.966064E+00 | -1.709609E+02 |
| 3.781900E+09 | -4.633545E+00 | -4.005664E+01 | -3.831421E+00 | 1.786719E+02 |
| 3.831250E+09 | -4.815674E+00 | -5.155273E+01 | -3.702026E+00 | 1.683437E+02 |
| 3.880600E+09 | -5.059570E+00 | -6.320313E+01 | -3.565186E+00 | 1.579062E+02 |
| 3.929950E+09 | -5.353271E+00 | -7.474218E+01 | -3.449219E+00 | 1.470703E+02 |
| 3.979300E+09 | -5.742920E+00 | -8.653906E+01 | -3.247559E+00 | 1.362500E+02 |
| 4.028650E+09 | -6.192627E+00 | -9.834373E+01 | -3.126343E+00 | 1.255195E+02 |
| 4.078000E+09 | -6.742432E+00 | -1.102695E+02 | -2.994995E+00 | 1.144453E+02 |
| 4.127350E+09 | -7.385254E+00 | -1.223867E+02 | -2.831055E+00 | 1.033672E+02 |
| 4.176700E+09 | -8.163086E+00 | -1.344531E+02 | -2.688721E+00 | 9.226563E+01 |
| 4.226050E+09 | -9.053711E+00 | -1.467187E+02 | -2.568481E+00 | 8.097656E+01 |
| 4.275400E+09 | -1.009863E+01 | -1.588359E+02 | -2.426514E+00 | 6.947656E+01 |
| 4.324750E+09 | -1.135107E+01 | -1.710312E+02 | -2.299072E+00 | 5.812304E+01 |
| 4.374100E+09 | -1.295459E+01 | 1.771563E+02 | -2.211670E+00 | 4.658789E+01 |
| 4.423450E+09 | -1.482861E+01 | 1.677344E+02 | -2.118286E+00 | 3.500781E+01 |
| 4.472800E+09 | -1.681738E+01 | 1.614453E+02 | -2.019531E+00 | 2.339942E+01 |
| 4.522150E+09 | -1.861426E+01 | 1.588438E+02 | -1.962952E+00 | 1.180029E+01 |
| 4.571500E+09 | -2.015527E+01 | 1.580547E+02 | -1.909973E+00 | 4.531860E-02 |
| 4.620850E+09 | -2.131054E+01 | 1.576484E+02 | -1.856506E+00 | -1.177637E+01 |
| 4.670200E+09 | -2.211035E+01 | 1.583281E+02 | -1.828308E+00 | -2.355273E+01 |
| 4.719550E+09 | -2.269726E+01 | 1.592734E+02 | -1.812256E+00 | -3.541406E+01 |
| 4.768900E+09 | -2.297168E+01 | 1.602813E+02 | -1.811035E+00 | -4.725195E+01 |
| 4.818250E+09 | -2.296973E+01 | 1.613125E+02 | -1.819458E+00 | -5.914648E+01 |
| 4.867600E+09 | -2.259375E+01 | 1.621719E+02 | -1.835632E+00 | -7.106250E+01 |
| 4.916950E+09 | -2.173438E+01 | 1.628515E+02 | -1.867554E+00 | -8.307421E+01 |
| 4.966300E+09 | -2.048730E+01 | 1.610547E+02 | -1.913635E+00 | -9.518358E+01 |
| 5.015650E+09 | -1.898828E+01 | 1.558750E+02 | -1.968628E+00 | -1.073476E+02 |
| 5.065000E+09 | -1.752441E+01 | 1.470625E+02 | -2.038452E+00 | -1.196055E+02 |
| 5.114350E+09 | -1.620410E+01 | 1.363437E+02 | -2.116699E+00 | -1.320000E+02 |
| 5.163700E+09 | -1.512207E+01 | 1.251406E+02 | -2.211670E+00 | -1.444609E+02 |
| 5.213050E+09 | -1.425439E+01 | 1.128398E+02 | -2.314941E+00 | -1.570469E+02 |
| 5.262400E+09 | -1.344580E+01 | 1.002226E+02 | -2.435059E+00 | -1.697969E+02 |

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|---|---|---|---|---|
| 5.311750E+09 | -1.284180E+01 | 8.770702E+01 | -2.557983E+00 | 1.772969E+02 |
| 5.361100E+09 | -1.235449E+01 | 7.501953E+01 | -2.698486E+00 | 1.642187E+02 |
| 5.410450E+09 | -1.204932E+01 | 6.298828E+01 | -2.842529E+00 | 1.509297E+02 |
| 5.459800E+09 | -1.194043E+01 | 5.137890E+01 | -3.001709E+00 | 1.374453E+02 |
| 5.509150E+09 | -1.194531E+01 | 4.108203E+01 | -3.177612E+00 | 1.235938E+02 |
| 5.558500E+09 | -1.207520E+01 | 3.247461E+01 | -3.370728E+00 | 1.094687E+02 |
| 5.607850E+09 | -1.214209E+01 | 2.552343E+01 | -3.591553E+00 | 9.498047E+01 |
| 5.657200E+09 | -1.206152E+01 | 1.980371E+01 | -3.864624E+00 | 8.017578E+01 |
| 5.706550E+09 | -1.184521E+01 | 1.483398E+01 | -4.175293E+00 | 6.503906E+01 |
| 5.755900E+09 | -1.151123E+01 | 1.020605E+01 | -4.541016E+00 | 4.970898E+01 |
| 5.805250E+09 | -1.108154E+01 | 5.603027E+00 | -4.990723E+00 | 3.431250E+01 |
| 5.854600E+09 | -1.052881E+01 | 1.098633E+00 | -5.489014E+00 | 1.858301E+01 |
| 5.903950E+09 | -9.888184E+00 | -3.379761E+00 | -6.023926E+00 | 3.033569E+00 |
| 5.953300E+09 | -9.145508E+00 | -8.270020E+00 | -6.652588E+00 | -1.241064E+01 |
| 6.002650E+09 | -8.251465E+00 | -1.366699E+01 | -7.308105E+00 | -2.788281E+01 |
| 6.052000E+09 | -7.282959E+00 | -2.014258E+01 | -7.979492E+00 | -4.289063E+01 |
| 6.101350E+09 | -6.252441E+00 | -2.810351E+01 | -8.695313E+00 | -5.749413E+01 |
| 6.150700E+09 | -5.332520E+00 | -3.744141E+01 | -9.400391E+00 | -7.163280E+01 |
| 6.200050E+09 | -4.600586E+00 | -4.777929E+01 | -1.009521E+01 | -8.534374E+01 |
| 6.249400E+09 | -4.032471E+00 | -5.855469E+01 | -1.072266E+01 | -9.861328E+01 |
| 6.298750E+09 | -3.619385E+00 | -6.949219E+01 | -1.131982E+01 | -1.112070E+02 |
| 6.348100E+09 | -3.306396E+00 | -8.029688E+01 | -1.180566E+01 | -1.238906E+02 |
| 6.397450E+09 | -3.083984E+00 | -9.104296E+01 | -1.220752E+01 | -1.358359E+02 |
| 6.446800E+09 | -2.936523E+00 | -1.017266E+02 | -1.253809E+01 | -1.476406E+02 |
| 6.496150E+09 | -2.841187E+00 | -1.123945E+02 | -1.277295E+01 | -1.592813E+02 |
| 6.545500E+09 | -2.799316E+00 | -1.230859E+02 | -1.292041E+01 | -1.707187E+02 |
| 6.594850E+09 | -2.787964E+00 | -1.338047E+02 | -1.298193E+01 | 1.781094E+02 |
| 6.644200E+09 | -2.813721E+00 | -1.445469E+02 | -1.295117E+01 | 1.668828E+02 |
| 6.693550E+09 | -2.880493E+00 | -1.555469E+02 | -1.285107E+01 | 1.556406E+02 |
| 6.742900E+09 | -2.971313E+00 | -1.667344E+02 | -1.263721E+01 | 1.444219E+02 |
| 6.792250E+09 | -3.099976E+00 | -1.781641E+02 | -1.240332E+01 | 1.333359E+02 |
| 6.841600E+09 | -3.247925E+00 | 1.701250E+02 | -1.208252E+01 | 1.217695E+02 |
| 6.890950E+09 | -3.427368E+00 | 1.580937E+02 | -1.171191E+01 | 1.106523E+02 |
| 6.940300E+09 | -3.636475E+00 | 1.456797E+02 | -1.134521E+01 | 9.906639E+01 |
| 6.989650E+09 | -3.863525E+00 | 1.330078E+02 | -1.092139E+01 | 8.739061E+01 |
| 7.039000E+09 | -4.112061E+00 | 1.200391E+02 | -1.045605E+01 | 7.568749E+01 |
| 7.088350E+09 | -4.370117E+00 | 1.068359E+02 | -9.986328E+00 | 6.383789E+01 |
| 7.137700E+09 | -4.636230E+00 | 9.338282E+01 | -9.559082E+00 | 5.164453E+01 |
| 7.187050E+09 | -4.907959E+00 | 7.971484E+01 | -9.106445E+00 | 3.919336E+01 |
| 7.236400E+09 | -5.166260E+00 | 6.593359E+01 | -8.624023E+00 | 2.681055E+01 |
| 7.285750E+09 | -5.409668E+00 | 5.207617E+01 | -8.249512E+00 | 1.458838E+01 |
| 7.335100E+09 | -5.646729E+00 | 3.824023E+01 | -7.892822E+00 | 1.533936E+00 |
| 7.384450E+09 | -5.886719E+00 | 2.443554E+01 | -7.501465E+00 | -1.107715E+01 |
| 7.433800E+09 | -6.104980E+00 | 1.072949E+01 | -7.224609E+00 | -2.366504E+01 |
| 7.483150E+09 | -6.330566E+00 | -2.569458E+00 | -6.963379E+00 | -3.634570E+01 |
| 7.532500E+09 | -6.580078E+00 | -1.570117E+01 | -6.730225E+00 | -4.912304E+01 |
| 7.581850E+09 | -6.860107E+00 | -2.851953E+01 | -6.508057E+00 | -6.156640E+01 |
| 7.631200E+09 | -7.192383E+00 | -4.094336E+01 | -6.334229E+00 | -7.388672E+01 |
| 7.680550E+09 | -7.588623E+00 | -5.274023E+01 | -6.146973E+00 | -8.633204E+01 |

| | | | | |
|---|---|---|---|---|
| 7.729900E+09 | -8.115723E+00 | -6.359765E+01 | -5.961914E+00 | -9.859764E+01 |
| 7.779250E+09 | -8.813477E+00 | -7.329296E+01 | -5.848633E+00 | -1.108555E+02 |
| 7.828600E+09 | -9.563477E+00 | -8.099218E+01 | -5.687500E+00 | -1.237930E+02 |
| 7.877950E+09 | -1.025342E+01 | -8.626562E+01 | -5.519043E+00 | -1.359375E+02 |
| 7.927300E+09 | -1.076709E+01 | -8.967968E+01 | -5.462891E+00 | -1.488125E+02 |
| 7.976650E+09 | -1.110156E+01 | -9.208984E+01 | -5.373047E+00 | -1.618906E+02 |
| 8.026000E+09 | -1.124854E+01 | -9.428905E+01 | -5.320068E+00 | -1.748672E+02 |
| 8.075350E+09 | -1.122314E+01 | -9.603905E+01 | -5.347412E+00 | 1.722109E+02 |
| 8.124700E+09 | -1.107715E+01 | -9.746094E+01 | -5.419678E+00 | 1.588516E+02 |
| 8.174050E+09 | -1.081201E+01 | -9.903515E+01 | -5.553711E+00 | 1.458047E+02 |
| 8.223400E+09 | -1.041748E+01 | -1.007930E+02 | -5.676270E+00 | 1.326562E+02 |
| 8.272750E+09 | -9.851563E+00 | -1.029883E+02 | -5.900391E+00 | 1.200469E+02 |
| 8.322100E+09 | -9.103516E+00 | -1.058359E+02 | -6.111816E+00 | 1.070313E+02 |
| 8.371450E+09 | -8.346680E+00 | -1.103086E+02 | -6.364502E+00 | 9.500391E+01 |
| 8.420800E+09 | -7.659180E+00 | -1.169375E+02 | -6.581055E+00 | 8.225780E+01 |
| 8.470150E+09 | -7.173340E+00 | -1.246016E+02 | -6.788086E+00 | 7.041406E+01 |
| 8.519500E+09 | -6.971924E+00 | -1.325312E+02 | -6.982910E+00 | 5.803515E+01 |
| 8.568850E+09 | -7.021240E+00 | -1.400938E+02 | -7.137695E+00 | 4.555078E+01 |
| 8.618200E+09 | -7.214844E+00 | -1.467031E+02 | -7.255127E+00 | 3.293359E+01 |
| 8.667550E+09 | -7.440674E+00 | -1.520781E+02 | -7.446777E+00 | 1.987109E+01 |
| 8.716900E+09 | -7.625488E+00 | -1.561797E+02 | -7.535645E+00 | 6.049316E+00 |
| 8.766250E+09 | -7.760986E+00 | -1.598828E+02 | -7.780518E+00 | -7.764648E+00 |
| 8.815600E+09 | -7.808838E+00 | -1.634766E+02 | -8.003906E+00 | -2.237011E+01 |
| 8.864950E+09 | -7.785889E+00 | -1.669062E+02 | -8.348145E+00 | -3.711523E+01 |
| 8.914300E+09 | -7.682617E+00 | -1.704609E+02 | -8.690430E+00 | -5.234375E+01 |
| 8.963650E+09 | -7.511230E+00 | -1.741719E+02 | -9.229492E+00 | -6.723046E+01 |
| 9.013000E+09 | -7.284424E+00 | -1.784297E+02 | -9.765137E+00 | -8.282421E+01 |
| 9.062350E+09 | -6.936279E+00 | 1.767266E+02 | -1.041943E+01 | -9.797655E+01 |
| 9.111700E+09 | -6.517822E+00 | 1.711406E+02 | -1.111328E+01 | -1.129570E+02 |
| 9.161050E+09 | -6.089844E+00 | 1.638906E+02 | -1.188721E+01 | -1.281719E+02 |
| 9.210400E+09 | -5.699951E+00 | 1.549922E+02 | -1.259229E+01 | -1.430078E+02 |
| 9.259750E+09 | -5.468506E+00 | 1.445781E+02 | -1.341406E+01 | -1.576172E+02 |
| 9.309100E+09 | -5.369385E+00 | 1.329297E+02 | -1.412500E+01 | -1.725703E+02 |
| 9.358450E+09 | -5.404053E+00 | 1.203906E+02 | -1.490820E+01 | 1.724062E+02 |
| 9.407800E+09 | -5.545410E+00 | 1.067539E+02 | -1.558740E+01 | 1.571484E+02 |
| 9.457150E+09 | -5.747070E+00 | 9.235546E+01 | -1.629492E+01 | 1.416563E+02 |
| 9.506500E+09 | -5.988037E+00 | 7.691015E+01 | -1.690137E+01 | 1.257656E+02 |
| 9.555850E+09 | -6.200684E+00 | 6.071289E+01 | -1.751172E+01 | 1.098398E+02 |
| 9.605200E+09 | -6.412354E+00 | 4.382226E+01 | -1.804394E+01 | 9.331249E+01 |
| 9.654550E+09 | -6.547852E+00 | 2.635449E+01 | -1.851465E+01 | 7.659765E+01 |
| 9.703900E+09 | -6.634033E+00 | 8.830078E+00 | -1.891113E+01 | 5.995703E+01 |
| 9.753250E+09 | -6.666504E+00 | -9.007813E+00 | -1.930859E+01 | 4.329883E+01 |
| 9.802600E+09 | -6.629395E+00 | -2.555761E+01 | -1.961621E+01 | 2.803515E+01 |
| 9.851950E+09 | -6.560791E+00 | -4.046094E+01 | -1.990723E+01 | 1.446045E+01 |
| 9.901300E+09 | -6.458740E+00 | -5.384179E+01 | -2.009277E+01 | 2.367554E+00 |
| 9.950650E+09 | -6.324707E+00 | -6.547265E+01 | -2.026562E+01 | -7.955566E+00 |
| 1.000000E+10 | -6.161133E+00 | -7.537109E+01 | -2.037402E+01 | -1.693066E+01 |

## A.9. 156-mil wide N-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.682617E+01 | -1.382891E+02 | -1.506195E-01 | -3.969922E+01 |
| 1.793500E+08 | -1.620215E+01 | -1.443047E+02 | -1.827240E-01 | -4.494531E+01 |
| 2.287000E+08 | -1.556738E+01 | -1.512969E+02 | -2.175903E-01 | -5.103516E+01 |
| 2.780500E+08 | -1.495068E+01 | -1.592578E+02 | -2.541504E-01 | -5.800781E+01 |
| 3.274000E+08 | -1.436133E+01 | -1.682188E+02 | -2.863159E-01 | -6.584374E+01 |
| 3.767500E+08 | -1.381934E+01 | -1.781797E+02 | -3.202057E-01 | -7.452734E+01 |
| 4.261000E+08 | -1.335596E+01 | 1.709063E+02 | -3.516235E-01 | -8.410547E+01 |
| 4.754500E+08 | -1.320703E+01 | 1.599375E+02 | -3.768463E-01 | -9.367968E+01 |
| 5.248000E+08 | -1.335840E+01 | 1.490234E+02 | -3.893890E-01 | -1.032539E+02 |
| 5.741500E+08 | -1.381641E+01 | 1.379688E+02 | -3.959961E-01 | -1.128906E+02 |
| 6.235000E+08 | -1.464355E+01 | 1.269492E+02 | -3.888397E-01 | -1.225898E+02 |
| 6.728500E+08 | -1.603223E+01 | 1.160078E+02 | -3.818512E-01 | -1.323359E+02 |
| 7.222000E+08 | -1.904492E+01 | 1.094727E+02 | -3.755646E-01 | -1.421641E+02 |
| 7.715500E+08 | -2.063574E+01 | 1.138164E+02 | -3.617401E-01 | -1.520625E+02 |
| 8.209000E+08 | -2.165820E+01 | 1.182656E+02 | -3.523254E-01 | -1.620156E+02 |
| 8.702500E+08 | -2.233984E+01 | 1.227851E+02 | -3.559418E-01 | -1.720547E+02 |
| 9.196000E+08 | -2.279785E+01 | 1.273516E+02 | -3.567657E-01 | 1.778437E+02 |
| 9.689500E+08 | -2.304004E+01 | 1.317422E+02 | -3.611298E-01 | 1.677266E+02 |
| 1.018300E+09 | -2.308789E+01 | 1.362422E+02 | -3.766632E-01 | 1.575859E+02 |
| 1.067650E+09 | -2.294824E+01 | 1.406016E+02 | -3.909912E-01 | 1.473906E+02 |
| 1.117000E+09 | -2.257422E+01 | 1.450156E+02 | -4.125824E-01 | 1.371875E+02 |
| 1.166350E+09 | -2.191992E+01 | 1.494141E+02 | -4.373474E-01 | 1.269922E+02 |
| 1.215700E+09 | -2.077246E+01 | 1.535312E+02 | -4.716949E-01 | 1.167851E+02 |
| 1.265050E+09 | -1.807031E+01 | 1.532578E+02 | -4.909058E-01 | 1.065430E+02 |
| 1.314400E+09 | -1.689551E+01 | 1.419688E+02 | -5.163879E-01 | 9.632813E+01 |
| 1.363750E+09 | -1.638574E+01 | 1.303125E+02 | -5.376282E-01 | 8.606640E+01 |
| 1.413100E+09 | -1.633594E+01 | 1.185156E+02 | -5.499268E-01 | 7.577343E+01 |
| 1.462450E+09 | -1.667676E+01 | 1.064297E+02 | -5.660400E-01 | 6.543359E+01 |
| 1.511800E+09 | -1.742383E+01 | 9.390625E+01 | -5.811768E-01 | 5.499023E+01 |
| 1.561150E+09 | -1.864062E+01 | 7.980859E+01 | -5.873108E-01 | 4.449414E+01 |
| 1.610500E+09 | -2.036133E+01 | 6.230469E+01 | -6.057739E-01 | 3.396289E+01 |
| 1.659850E+09 | -2.186133E+01 | 3.893945E+01 | -6.197510E-01 | 2.340137E+01 |
| 1.709200E+09 | -2.309668E+01 | 1.447412E+01 | -6.413269E-01 | 1.277295E+01 |
| 1.758550E+09 | -2.416308E+01 | -1.041504E+01 | -6.522827E-01 | 2.081909E+00 |
| 1.807900E+09 | -2.508984E+01 | -3.423633E+01 | -6.806946E-01 | -8.631348E+00 |
| 1.857250E+09 | -2.581640E+01 | -5.786914E+01 | -7.088013E-01 | -1.938281E+01 |
| 1.906600E+09 | -2.642090E+01 | -8.041407E+01 | -7.432251E-01 | -3.014648E+01 |
| 1.955950E+09 | -2.686426E+01 | -1.007617E+02 | -7.800903E-01 | -4.098046E+01 |
| 2.005300E+09 | -2.696191E+01 | -1.198125E+02 | -8.199768E-01 | -5.183398E+01 |
| 2.054650E+09 | -2.661523E+01 | -1.369219E+02 | -8.648987E-01 | -6.262500E+01 |
| 2.104000E+09 | -2.572558E+01 | -1.510391E+02 | -9.139404E-01 | -7.346484E+01 |
| 2.153350E+09 | -2.419922E+01 | -1.607891E+02 | -9.533081E-01 | -8.426952E+01 |
| 2.202700E+09 | -2.268555E+01 | -1.639609E+02 | -1.000549E+00 | -9.510157E+01 |
| 2.252050E+09 | -2.126563E+01 | -1.657969E+02 | -1.057129E+00 | -1.060547E+02 |
| 2.301400E+09 | -1.984082E+01 | -1.669922E+02 | -1.115356E+00 | -1.169609E+02 |
| 2.350750E+09 | -1.841601E+01 | -1.691953E+02 | -1.185486E+00 | -1.278242E+02 |

| | | | | |
|---|---|---|---|---|
| 2.400100E+09 | -1.702148E+01 | -1.713594E+02 | -1.270264E+00 | -1.387266E+02 |
| 2.449450E+09 | -1.557031E+01 | -1.742422E+02 | -1.356262E+00 | -1.495625E+02 |
| 2.498800E+09 | -1.407324E+01 | -1.790859E+02 | -1.460876E+00 | -1.601484E+02 |
| 2.548150E+09 | -1.264600E+01 | 1.751016E+02 | -1.559937E+00 | -1.707969E+02 |
| 2.597500E+09 | -1.135938E+01 | 1.680156E+02 | -1.696838E+00 | 1.787109E+02 |
| 2.646850E+09 | -1.021191E+01 | 1.594844E+02 | -1.808472E+00 | 1.681484E+02 |
| 2.696200E+09 | -9.224609E+00 | 1.502656E+02 | -1.937622E+00 | 1.580391E+02 |
| 2.745550E+09 | -8.475586E+00 | 1.404375E+02 | -2.090454E+00 | 1.478125E+02 |
| 2.794900E+09 | -7.878174E+00 | 1.305391E+02 | -2.184570E+00 | 1.380391E+02 |
| 2.844250E+09 | -7.446533E+00 | 1.206641E+02 | -2.316406E+00 | 1.283203E+02 |
| 2.893600E+09 | -7.118652E+00 | 1.107422E+02 | -2.407227E+00 | 1.187891E+02 |
| 2.942950E+09 | -6.889648E+00 | 1.008047E+02 | -2.489624E+00 | 1.093281E+02 |
| 2.992300E+09 | -6.757080E+00 | 9.077734E+01 | -2.542480E+00 | 9.992577E+01 |
| 3.041650E+09 | -6.736572E+00 | 8.060547E+01 | -2.565430E+00 | 9.060547E+01 |
| 3.091000E+09 | -6.832520E+00 | 7.048437E+01 | -2.583252E+00 | 8.152735E+01 |
| 3.140350E+09 | -7.030029E+00 | 6.021484E+01 | -2.541016E+00 | 7.216797E+01 |
| 3.189700E+09 | -7.348633E+00 | 4.998828E+01 | -2.475708E+00 | 6.315624E+01 |
| 3.239050E+09 | -7.784912E+00 | 3.972851E+01 | -2.421265E+00 | 5.367188E+01 |
| 3.288400E+09 | -8.301758E+00 | 2.938965E+01 | -2.306030E+00 | 4.433203E+01 |
| 3.337750E+09 | -8.974609E+00 | 1.864453E+01 | -2.223877E+00 | 3.475195E+01 |
| 3.387100E+09 | -9.797363E+00 | 7.764404E+00 | -2.080444E+00 | 2.515137E+01 |
| 3.436450E+09 | -1.085645E+01 | -3.313843E+00 | -1.971313E+00 | 1.531738E+01 |
| 3.485800E+09 | -1.213672E+01 | -1.476709E+01 | -1.840149E+00 | 5.354248E+00 |
| 3.535150E+09 | -1.372607E+01 | -2.608105E+01 | -1.727905E+00 | -4.641846E+00 |
| 3.584500E+09 | -1.569824E+01 | -3.894336E+01 | -1.626221E+00 | -1.494141E+01 |
| 3.633850E+09 | -1.784668E+01 | -5.269531E+01 | -1.523315E+00 | -2.542578E+01 |
| 3.683200E+09 | -2.051660E+01 | -7.030078E+01 | -1.440063E+00 | -3.575781E+01 |
| 3.732550E+09 | -2.277832E+01 | -9.021484E+01 | -1.403259E+00 | -4.631055E+01 |
| 3.781900E+09 | -2.498242E+01 | -1.099805E+02 | -1.341064E+00 | -5.684375E+01 |
| 3.831250E+09 | -2.687500E+01 | -1.292422E+02 | -1.307556E+00 | -6.744531E+01 |
| 3.880600E+09 | -2.844922E+01 | -1.450781E+02 | -1.291870E+00 | -7.812500E+01 |
| 3.929950E+09 | -2.960058E+01 | -1.593594E+02 | -1.299438E+00 | -8.887499E+01 |
| 3.979300E+09 | -3.020020E+01 | -1.731172E+02 | -1.302490E+00 | -9.957811E+01 |
| 4.028650E+09 | -3.031152E+01 | 1.740859E+02 | -1.323120E+00 | -1.102969E+02 |
| 4.078000E+09 | -2.988183E+01 | 1.613750E+02 | -1.350891E+00 | -1.210703E+02 |
| 4.127350E+09 | -2.889453E+01 | 1.504062E+02 | -1.391113E+00 | -1.318359E+02 |
| 4.176700E+09 | -2.756836E+01 | 1.403516E+02 | -1.441956E+00 | -1.426328E+02 |
| 4.226050E+09 | -2.557324E+01 | 1.345234E+02 | -1.495605E+00 | -1.534844E+02 |
| 4.275400E+09 | -2.387988E+01 | 1.311250E+02 | -1.549072E+00 | -1.643750E+02 |
| 4.324750E+09 | -2.207910E+01 | 1.276992E+02 | -1.623169E+00 | -1.754062E+02 |
| 4.374100E+09 | -2.050586E+01 | 1.242773E+02 | -1.692749E+00 | 1.735625E+02 |
| 4.423450E+09 | -1.914160E+01 | 1.181602E+02 | -1.768433E+00 | 1.624922E+02 |
| 4.472800E+09 | -1.806836E+01 | 1.111953E+02 | -1.851074E+00 | 1.513281E+02 |
| 4.522150E+09 | -1.735449E+01 | 1.051601E+02 | -1.936340E+00 | 1.400312E+02 |
| 4.571500E+09 | -1.688086E+01 | 9.967577E+01 | -2.034790E+00 | 1.287031E+02 |
| 4.620850E+09 | -1.650195E+01 | 9.539454E+01 | -2.141846E+00 | 1.172656E+02 |
| 4.670200E+09 | -1.620410E+01 | 9.234375E+01 | -2.246948E+00 | 1.057500E+02 |
| 4.719550E+09 | -1.584717E+01 | 9.028515E+01 | -2.359253E+00 | 9.410156E+01 |
| 4.768900E+09 | -1.538721E+01 | 8.860546E+01 | -2.494995E+00 | 8.235546E+01 |

| | | | | |
|---|---|---|---|---|
| 4.818250E+09 | -1.479346E+01 | 8.711329E+01 | -2.654663E+00 | 7.044922E+01 |
| 4.867600E+09 | -1.415283E+01 | 8.558203E+01 | -2.820068E+00 | 5.863086E+01 |
| 4.916950E+09 | -1.344482E+01 | 8.374609E+01 | -3.021973E+00 | 4.681641E+01 |
| 4.966300E+09 | -1.261133E+01 | 8.158594E+01 | -3.234009E+00 | 3.496484E+01 |
| 5.015650E+09 | -1.169531E+01 | 7.905468E+01 | -3.457031E+00 | 2.321387E+01 |
| 5.065000E+09 | -1.068945E+01 | 7.531250E+01 | -3.710938E+00 | 1.156152E+01 |
| 5.114350E+09 | -9.638184E+00 | 7.050390E+01 | -3.971680E+00 | 4.394531E-02 |
| 5.163700E+09 | -8.665039E+00 | 6.435156E+01 | -4.229004E+00 | -1.125830E+01 |
| 5.213050E+09 | -7.717041E+00 | 5.690039E+01 | -4.486816E+00 | -2.230371E+01 |
| 5.262400E+09 | -6.926514E+00 | 4.849023E+01 | -4.733154E+00 | -3.316406E+01 |
| 5.311750E+09 | -6.321289E+00 | 3.938672E+01 | -4.947998E+00 | -4.378711E+01 |
| 5.361100E+09 | -5.853760E+00 | 3.015820E+01 | -5.153076E+00 | -5.414453E+01 |
| 5.410450E+09 | -5.520508E+00 | 2.088769E+01 | -5.294434E+00 | -6.444530E+01 |
| 5.459800E+09 | -5.273682E+00 | 1.147656E+01 | -5.402832E+00 | -7.444140E+01 |
| 5.509150E+09 | -5.134521E+00 | 2.025513E+00 | -5.483887E+00 | -8.439062E+01 |
| 5.558500E+09 | -5.083984E+00 | -7.707031E+00 | -5.507324E+00 | -9.432421E+01 |
| 5.607850E+09 | -5.109131E+00 | -1.743164E+01 | -5.476318E+00 | -1.041211E+02 |
| 5.657200E+09 | -5.255371E+00 | -2.737305E+01 | -5.397461E+00 | -1.139883E+02 |
| 5.706550E+09 | -5.489014E+00 | -3.747461E+01 | -5.280029E+00 | -1.240351E+02 |
| 5.755900E+09 | -5.836182E+00 | -4.776757E+01 | -5.120850E+00 | -1.342891E+02 |
| 5.805250E+09 | -6.292725E+00 | -5.835546E+01 | -4.945068E+00 | -1.445313E+02 |
| 5.854600E+09 | -6.867432E+00 | -6.901953E+01 | -4.759277E+00 | -1.550234E+02 |
| 5.903950E+09 | -7.583252E+00 | -8.017187E+01 | -4.528809E+00 | -1.656953E+02 |
| 5.953300E+09 | -8.416016E+00 | -9.164063E+01 | -4.320313E+00 | -1.764766E+02 |
| 6.002650E+09 | -9.448730E+00 | -1.036523E+02 | -4.100586E+00 | 1.723516E+02 |
| 6.052000E+09 | -1.059131E+01 | -1.164336E+02 | -3.875244E+00 | 1.610547E+02 |
| 6.101350E+09 | -1.183594E+01 | -1.291719E+02 | -3.683960E+00 | 1.496797E+02 |
| 6.150700E+09 | -1.315283E+01 | -1.431484E+02 | -3.498413E+00 | 1.380703E+02 |
| 6.200050E+09 | -1.433643E+01 | -1.575156E+02 | -3.341187E+00 | 1.263867E+02 |
| 6.249400E+09 | -1.543848E+01 | -1.724062E+02 | -3.211060E+00 | 1.146289E+02 |
| 6.298750E+09 | -1.628515E+01 | 1.724688E+02 | -3.109863E+00 | 1.028477E+02 |
| 6.348100E+09 | -1.691308E+01 | 1.574219E+02 | -3.033813E+00 | 9.097656E+01 |
| 6.397450E+09 | -1.729394E+01 | 1.422500E+02 | -2.983765E+00 | 7.906640E+01 |
| 6.446800E+09 | -1.740918E+01 | 1.273320E+02 | -2.962891E+00 | 6.726563E+01 |
| 6.496150E+09 | -1.726953E+01 | 1.126133E+02 | -2.960327E+00 | 5.547461E+01 |
| 6.545500E+09 | -1.679980E+01 | 9.842186E+01 | -2.974121E+00 | 4.381055E+01 |
| 6.594850E+09 | -1.613281E+01 | 8.489452E+01 | -3.012329E+00 | 3.213086E+01 |
| 6.644200E+09 | -1.525586E+01 | 7.127734E+01 | -3.057739E+00 | 2.049707E+01 |
| 6.693550E+09 | -1.423926E+01 | 5.896484E+01 | -3.119873E+00 | 8.934570E+00 |
| 6.742900E+09 | -1.325391E+01 | 4.704883E+01 | -3.201050E+00 | -2.576294E+00 |
| 6.792250E+09 | -1.227393E+01 | 3.585546E+01 | -3.281128E+00 | -1.403955E+01 |
| 6.841600E+09 | -1.147412E+01 | 2.504883E+01 | -3.375122E+00 | -2.535449E+01 |
| 6.890950E+09 | -1.081396E+01 | 1.434229E+01 | -3.463379E+00 | -3.677343E+01 |
| 6.940300E+09 | -1.034082E+01 | 4.266602E+00 | -3.533936E+00 | -4.798437E+01 |
| 6.989650E+09 | -1.009277E+01 | -5.572998E+00 | -3.611206E+00 | -5.936328E+01 |
| 7.039000E+09 | -1.004053E+01 | -1.472070E+01 | -3.697632E+00 | -7.078125E+01 |
| 7.088350E+09 | -1.022656E+01 | -2.278711E+01 | -3.783081E+00 | -8.228516E+01 |
| 7.137700E+09 | -1.056885E+01 | -2.946680E+01 | -3.853027E+00 | -9.370703E+01 |
| 7.187050E+09 | -1.097070E+01 | -3.403711E+01 | -3.935059E+00 | -1.053516E+02 |

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|---|---|---|---|---|
| 7.236400E+09 | -1.130127E+01 | -3.700586E+01 | -3.994141E+00 | -1.172422E+02 |
| 7.285750E+09 | -1.149121E+01 | -3.880664E+01 | -4.077637E+00 | -1.290078E+02 |
| 7.335100E+09 | -1.155127E+01 | -3.997265E+01 | -4.209961E+00 | -1.413672E+02 |
| 7.384450E+09 | -1.146582E+01 | -4.083398E+01 | -4.289307E+00 | -1.537344E+02 |
| 7.433800E+09 | -1.125293E+01 | -4.146484E+01 | -4.465332E+00 | -1.658437E+02 |
| 7.483150E+09 | -1.091455E+01 | -4.236133E+01 | -4.696289E+00 | -1.784141E+02 |
| 7.532500E+09 | -1.043359E+01 | -4.324804E+01 | -4.920410E+00 | 1.690156E+02 |
| 7.581850E+09 | -9.838379E+00 | -4.459180E+01 | -5.158936E+00 | 1.569844E+02 |
| 7.631200E+09 | -9.089355E+00 | -4.701367E+01 | -5.463379E+00 | 1.450234E+02 |
| 7.680550E+09 | -8.230469E+00 | -5.053320E+01 | -5.798828E+00 | 1.330703E+02 |
| 7.729900E+09 | -7.396240E+00 | -5.593359E+01 | -6.075195E+00 | 1.213711E+02 |
| 7.779250E+09 | -6.659912E+00 | -6.290820E+01 | -6.433105E+00 | 1.106484E+02 |
| 7.828600E+09 | -6.115479E+00 | -7.080468E+01 | -6.776123E+00 | 9.915625E+01 |
| 7.877950E+09 | -5.738770E+00 | -7.937500E+01 | -6.973389E+00 | 8.899609E+01 |
| 7.927300E+09 | -5.512695E+00 | -8.814062E+01 | -7.273682E+00 | 7.856640E+01 |
| 7.976650E+09 | -5.452881E+00 | -9.712109E+01 | -7.418701E+00 | 6.828906E+01 |
| 8.026000E+09 | -5.512207E+00 | -1.061680E+02 | -7.496826E+00 | 5.840820E+01 |
| 8.075350E+09 | -5.719727E+00 | -1.153242E+02 | -7.538818E+00 | 4.868945E+01 |
| 8.124700E+09 | -6.066895E+00 | -1.247695E+02 | -7.522705E+00 | 3.828711E+01 |
| 8.174050E+09 | -6.579346E+00 | -1.340937E+02 | -7.401367E+00 | 2.804883E+01 |
| 8.223400E+09 | -7.288818E+00 | -1.437578E+02 | -7.232178E+00 | 1.739062E+01 |
| 8.272750E+09 | -8.205566E+00 | -1.531172E+02 | -7.065430E+00 | 6.744141E+00 |
| 8.322100E+09 | -9.479492E+00 | -1.624219E+02 | -6.827637E+00 | -4.998779E+00 |
| 8.371450E+09 | -1.092578E+01 | -1.717422E+02 | -6.539551E+00 | -1.612109E+01 |
| 8.420800E+09 | -1.266113E+01 | -1.796953E+02 | -6.338379E+00 | -2.834473E+01 |
| 8.470150E+09 | -1.526123E+01 | 1.715312E+02 | -6.061279E+00 | -4.040820E+01 |
| 8.519500E+09 | -1.785840E+01 | 1.568281E+02 | -5.844238E+00 | -5.305469E+01 |
| 8.568850E+09 | -1.973437E+01 | 1.378672E+02 | -5.639160E+00 | -6.593750E+01 |
| 8.618200E+09 | -2.094531E+01 | 1.190312E+02 | -5.462402E+00 | -7.901953E+01 |
| 8.667550E+09 | -2.174609E+01 | 9.989843E+01 | -5.335938E+00 | -9.223047E+01 |
| 8.716900E+09 | -2.209570E+01 | 8.076952E+01 | -5.241211E+00 | -1.056055E+02 |
| 8.766250E+09 | -2.207715E+01 | 6.185937E+01 | -5.206055E+00 | -1.188984E+02 |
| 8.815600E+09 | -2.167383E+01 | 4.225976E+01 | -5.229980E+00 | -1.322734E+02 |
| 8.864950E+09 | -2.078906E+01 | 2.263867E+01 | -5.271240E+00 | -1.454687E+02 |
| 8.914300E+09 | -1.961914E+01 | 2.797363E+00 | -5.376465E+00 | -1.584844E+02 |
| 8.963650E+09 | -1.805664E+01 | -1.842871E+01 | -5.518555E+00 | -1.713516E+02 |
| 9.013000E+09 | -1.556885E+01 | -3.892969E+01 | -5.680908E+00 | 1.761094E+02 |
| 9.062350E+09 | -1.297168E+01 | -5.350976E+01 | -5.870361E+00 | 1.636797E+02 |
| 9.111700E+09 | -1.102979E+01 | -6.358398E+01 | -6.085693E+00 | 1.517422E+02 |
| 9.161050E+09 | -9.668945E+00 | -7.384375E+01 | -6.280029E+00 | 1.398906E+02 |
| 9.210400E+09 | -8.601563E+00 | -8.355078E+01 | -6.495605E+00 | 1.287266E+02 |
| 9.259750E+09 | -7.873291E+00 | -9.312891E+01 | -6.692871E+00 | 1.173164E+02 |
| 9.309100E+09 | -7.377686E+00 | -1.026133E+02 | -6.861816E+00 | 1.065820E+02 |
| 9.358450E+09 | -7.120605E+00 | -1.113359E+02 | -6.969971E+00 | 9.571093E+01 |
| 9.407800E+09 | -7.077393E+00 | -1.197773E+02 | -7.094482E+00 | 8.523438E+01 |
| 9.457150E+09 | -7.201416E+00 | -1.273750E+02 | -7.130127E+00 | 7.417578E+01 |
| 9.506500E+09 | -7.536377E+00 | -1.336641E+02 | -7.152588E+00 | 6.347851E+01 |
| 9.555850E+09 | -7.950439E+00 | -1.386875E+02 | -7.147217E+00 | 5.216406E+01 |
| 9.605200E+09 | -8.371582E+00 | -1.419688E+02 | -7.153076E+00 | 4.093750E+01 |

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|---|---|---|---|---|
| 9.654550E+09 | -8.688477E+00 | -1.442891E+02 | -7.136475E+00 | 2.917969E+01 |
| 9.703900E+09 | -8.863281E+00 | -1.457266E+02 | -7.201172E+00 | 1.736719E+01 |
| 9.753250E+09 | -8.952148E+00 | -1.467031E+02 | -7.251465E+00 | 5.140137E+00 |
| 9.802600E+09 | -9.015137E+00 | -1.469922E+02 | -7.320801E+00 | -5.822754E+00 |
| 9.851950E+09 | -9.039063E+00 | -1.465703E+02 | -7.378174E+00 | -1.607031E+01 |
| 9.901300E+09 | -8.990234E+00 | -1.457109E+02 | -7.477051E+00 | -2.515820E+01 |
| 9.950650E+09 | -8.855957E+00 | -1.443047E+02 | -7.545654E+00 | -3.342187E+01 |
| 1.000000E+10 | -8.646484E+00 | -1.427266E+02 | -7.658447E+00 | -4.025586E+01 |

## A.10. 156-mil wide M-shaped structure with 1S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.524707E+01 | -1.488594E+02 | -2.525482E-01 | -5.018555E+01 |
| 1.793500E+08 | -1.480273E+01 | -1.563125E+02 | -2.781372E-01 | -5.680859E+01 |
| 2.287000E+08 | -1.441211E+01 | -1.649765E+02 | -3.017883E-01 | -6.454687E+01 |
| 2.780500E+08 | -1.411328E+01 | -1.748672E+02 | -3.216400E-01 | -7.338281E+01 |
| 3.274000E+08 | -1.396240E+01 | 1.739922E+02 | -3.383026E-01 | -8.334375E+01 |
| 3.767500E+08 | -1.402051E+01 | 1.616172E+02 | -3.515778E-01 | -9.445704E+01 |
| 4.261000E+08 | -1.442969E+01 | 1.481641E+02 | -3.657379E-01 | -1.067226E+02 |
| 4.754500E+08 | -1.572852E+01 | 1.351797E+02 | -3.717499E-01 | -1.190391E+02 |
| 5.248000E+08 | -1.768164E+01 | 1.348750E+02 | -3.770752E-01 | -1.314141E+02 |
| 5.741500E+08 | -1.870996E+01 | 1.364766E+02 | -3.802948E-01 | -1.438672E+02 |
| 6.235000E+08 | -1.937304E+01 | 1.382813E+02 | -3.819885E-01 | -1.564062E+02 |
| 6.728500E+08 | -1.982617E+01 | 1.400703E+02 | -3.838348E-01 | -1.690078E+02 |
| 7.222000E+08 | -2.010547E+01 | 1.418437E+02 | -3.929749E-01 | 1.783203E+02 |
| 7.715500E+08 | -2.023730E+01 | 1.436328E+02 | -4.075317E-01 | 1.656172E+02 |
| 8.209000E+08 | -2.023633E+01 | 1.453594E+02 | -4.318695E-01 | 1.528984E+02 |
| 8.702500E+08 | -2.007715E+01 | 1.470469E+02 | -4.582825E-01 | 1.401562E+02 |
| 9.196000E+08 | -1.973633E+01 | 1.487656E+02 | -4.898376E-01 | 1.273984E+02 |
| 9.689500E+08 | -1.911816E+01 | 1.501875E+02 | -5.133362E-01 | 1.146250E+02 |
| 1.018300E+09 | -1.792969E+01 | 1.513125E+02 | -5.482788E-01 | 1.018984E+02 |
| 1.067650E+09 | -1.638379E+01 | 1.397891E+02 | -5.692749E-01 | 8.912500E+01 |
| 1.117000E+09 | -1.607812E+01 | 1.262812E+02 | -5.878601E-01 | 7.637500E+01 |
| 1.166350E+09 | -1.658301E+01 | 1.129883E+02 | -6.007690E-01 | 6.356640E+01 |
| 1.215700E+09 | -1.824414E+01 | 1.012226E+02 | -6.115723E-01 | 5.070703E+01 |
| 1.265050E+09 | -1.984277E+01 | 1.018437E+02 | -6.175537E-01 | 3.778711E+01 |
| 1.314400E+09 | -2.080371E+01 | 1.028984E+02 | -6.271362E-01 | 2.481054E+01 |
| 1.363750E+09 | -2.148730E+01 | 1.041562E+02 | -6.264954E-01 | 1.171924E+01 |
| 1.413100E+09 | -2.201758E+01 | 1.055391E+02 | -6.305847E-01 | -1.430969E+00 |
| 1.462450E+09 | -2.245312E+01 | 1.067305E+02 | -6.391907E-01 | -1.463818E+01 |
| 1.511800E+09 | -2.279297E+01 | 1.079336E+02 | -6.526489E-01 | -2.794238E+01 |
| 1.561150E+09 | -2.306933E+01 | 1.091680E+02 | -6.614685E-01 | -4.132226E+01 |
| 1.610500E+09 | -2.329688E+01 | 1.100312E+02 | -6.843262E-01 | -5.470508E+01 |
| 1.659850E+09 | -2.344043E+01 | 1.108594E+02 | -7.132568E-01 | -6.821484E+01 |
| 1.709200E+09 | -2.348340E+01 | 1.108594E+02 | -7.442322E-01 | -8.176172E+01 |
| 1.758550E+09 | -2.308789E+01 | 1.071719E+02 | -7.773438E-01 | -9.536327E+01 |
| 1.807900E+09 | -2.345996E+01 | 8.355078E+01 | -8.121643E-01 | -1.089844E+02 |
| 1.857250E+09 | -2.384277E+01 | 5.596680E+01 | -8.452454E-01 | -1.227070E+02 |

| | | | | |
|---|---|---|---|---|
| 1.906600E+09 | -2.421093E+01 | 2.759570E+01 | -8.863525E-01 | -1.364375E+02 |
| 1.955950E+09 | -2.456738E+01 | -1.040955E+00 | -9.349365E-01 | -1.502656E+02 |
| 2.005300E+09 | -2.498047E+01 | -2.879297E+01 | -9.834595E-01 | -1.641875E+02 |
| 2.054650E+09 | -2.537402E+01 | -5.524023E+01 | -1.041870E+00 | -1.780859E+02 |
| 2.104000E+09 | -2.574023E+01 | -7.986328E+01 | -1.108765E+00 | 1.678906E+02 |
| 2.153350E+09 | -2.586719E+01 | -1.018633E+02 | -1.169373E+00 | 1.538203E+02 |
| 2.202700E+09 | -2.552637E+01 | -1.223633E+02 | -1.244141E+00 | 1.397891E+02 |
| 2.252050E+09 | -2.463769E+01 | -1.410938E+02 | -1.331238E+00 | 1.256562E+02 |
| 2.301400E+09 | -2.301660E+01 | -1.573281E+02 | -1.421082E+00 | 1.115547E+02 |
| 2.350750E+09 | -2.064258E+01 | -1.655234E+02 | -1.526672E+00 | 9.740234E+01 |
| 2.400100E+09 | -1.885351E+01 | -1.700156E+02 | -1.646484E+00 | 8.323437E+01 |
| 2.449450E+09 | -1.727832E+01 | -1.737266E+02 | -1.785767E+00 | 6.908984E+01 |
| 2.498800E+09 | -1.577832E+01 | -1.771328E+02 | -1.947754E+00 | 5.510937E+01 |
| 2.548150E+09 | -1.422217E+01 | 1.788437E+02 | -2.116577E+00 | 4.119726E+01 |
| 2.597500E+09 | -1.266064E+01 | 1.738125E+02 | -2.332397E+00 | 2.754395E+01 |
| 2.646850E+09 | -1.104004E+01 | 1.669922E+02 | -2.514404E+00 | 1.384277E+01 |
| 2.696200E+09 | -9.508301E+00 | 1.580234E+02 | -2.738159E+00 | 7.814026E-01 |
| 2.745550E+09 | -8.285156E+00 | 1.478203E+02 | -2.965576E+00 | -1.245996E+01 |
| 2.794900E+09 | -7.299316E+00 | 1.365156E+02 | -3.138184E+00 | -2.509863E+01 |
| 2.844250E+09 | -6.549316E+00 | 1.250117E+02 | -3.351196E+00 | -3.757617E+01 |
| 2.893600E+09 | -6.013916E+00 | 1.131953E+02 | -3.517334E+00 | -4.970117E+01 |
| 2.942950E+09 | -5.631592E+00 | 1.012969E+02 | -3.668701E+00 | -6.159961E+01 |
| 2.992300E+09 | -5.416992E+00 | 8.935547E+01 | -3.747803E+00 | -7.333202E+01 |
| 3.041650E+09 | -5.368652E+00 | 7.728125E+01 | -3.779785E+00 | -8.487108E+01 |
| 3.091000E+09 | -5.461182E+00 | 6.532421E+01 | -3.779419E+00 | -9.630077E+01 |
| 3.140350E+09 | -5.691895E+00 | 5.326757E+01 | -3.699219E+00 | -1.081016E+02 |
| 3.189700E+09 | -6.071045E+00 | 4.110352E+01 | -3.588745E+00 | -1.195351E+02 |
| 3.239050E+09 | -6.624756E+00 | 2.883301E+01 | -3.446899E+00 | -1.315234E+02 |
| 3.288400E+09 | -7.375732E+00 | 1.622266E+01 | -3.245850E+00 | -1.435078E+02 |
| 3.337750E+09 | -8.380859E+00 | 3.479858E+00 | -3.075317E+00 | -1.558984E+02 |
| 3.387100E+09 | -9.692871E+00 | -9.139648E+00 | -2.839233E+00 | -1.684766E+02 |
| 3.436450E+09 | -1.136230E+01 | -2.142383E+01 | -2.637573E+00 | 1.786250E+02 |
| 3.485800E+09 | -1.355273E+01 | -3.343750E+01 | -2.431519E+00 | 1.655234E+02 |
| 3.535150E+09 | -1.612500E+01 | -4.330859E+01 | -2.274414E+00 | 1.522656E+02 |
| 3.584500E+09 | -2.000977E+01 | -4.565820E+01 | -2.132813E+00 | 1.387344E+02 |
| 3.633850E+09 | -2.339942E+01 | -3.635351E+01 | -2.008179E+00 | 1.251445E+02 |
| 3.683200E+09 | -2.772949E+01 | -2.581152E+01 | -1.912537E+00 | 1.116836E+02 |
| 3.732550E+09 | -3.022168E+01 | -1.216357E+01 | -1.863525E+00 | 9.802343E+01 |
| 3.781900E+09 | -3.190136E+01 | 3.401611E+00 | -1.814453E+00 | 8.436718E+01 |
| 3.831250E+09 | -3.312695E+01 | 1.945313E+01 | -1.800781E+00 | 7.085155E+01 |
| 3.880600E+09 | -3.378906E+01 | 3.548047E+01 | -1.799133E+00 | 5.734179E+01 |
| 3.929950E+09 | -3.405859E+01 | 5.168945E+01 | -1.817261E+00 | 4.393555E+01 |
| 3.979300E+09 | -3.386328E+01 | 6.758984E+01 | -1.837402E+00 | 3.049511E+01 |
| 4.028650E+09 | -3.311328E+01 | 8.351563E+01 | -1.853821E+00 | 1.712305E+01 |
| 4.078000E+09 | -3.195996E+01 | 9.763672E+01 | -1.875305E+00 | 3.765503E+00 |
| 4.127350E+09 | -2.956445E+01 | 1.052500E+02 | -1.896973E+00 | -9.598145E+00 |
| 4.176700E+09 | -2.784472E+01 | 1.028633E+02 | -1.921997E+00 | -2.305371E+01 |
| 4.226050E+09 | -2.504883E+01 | 1.026914E+02 | -1.950928E+00 | -3.657031E+01 |
| 4.275400E+09 | -2.364160E+01 | 1.025273E+02 | -1.991638E+00 | -5.015234E+01 |

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|---|---|---|---|---|
| 4.324750E+09 | -2.263574E+01 | 1.016445E+02 | -2.040771E+00 | -6.387890E+01 |
| 4.374100E+09 | -2.164453E+01 | 1.008789E+02 | -2.091919E+00 | -7.761719E+01 |
| 4.423450E+09 | -2.077539E+01 | 1.005703E+02 | -2.171753E+00 | -9.139452E+01 |
| 4.472800E+09 | -1.987305E+01 | 9.996483E+01 | -2.257080E+00 | -1.053516E+02 |
| 4.522150E+09 | -1.896875E+01 | 9.947266E+01 | -2.345703E+00 | -1.193125E+02 |
| 4.571500E+09 | -1.803125E+01 | 9.875780E+01 | -2.450684E+00 | -1.333203E+02 |
| 4.620850E+09 | -1.703906E+01 | 9.773438E+01 | -2.566162E+00 | -1.474922E+02 |
| 4.670200E+09 | -1.592188E+01 | 9.602343E+01 | -2.693726E+00 | -1.617188E+02 |
| 4.719550E+09 | -1.459424E+01 | 9.283983E+01 | -2.835815E+00 | -1.760313E+02 |
| 4.768900E+09 | -1.339502E+01 | 8.689844E+01 | -2.982666E+00 | 1.696094E+02 |
| 4.818250E+09 | -1.265820E+01 | 7.882421E+01 | -3.137207E+00 | 1.550547E+02 |
| 4.867600E+09 | -1.226611E+01 | 7.128515E+01 | -3.285034E+00 | 1.404141E+02 |
| 4.916950E+09 | -1.209180E+01 | 6.555469E+01 | -3.464722E+00 | 1.255469E+02 |
| 4.966300E+09 | -1.194580E+01 | 6.104882E+01 | -3.652954E+00 | 1.103828E+02 |
| 5.015650E+09 | -1.171729E+01 | 5.727539E+01 | -3.872437E+00 | 9.512110E+01 |
| 5.065000E+09 | -1.144727E+01 | 5.390038E+01 | -4.124023E+00 | 7.980859E+01 |
| 5.114350E+09 | -1.111279E+01 | 5.063867E+01 | -4.418945E+00 | 6.444140E+01 |
| 5.163700E+09 | -1.070459E+01 | 4.760351E+01 | -4.749756E+00 | 4.908984E+01 |
| 5.213050E+09 | -1.021973E+01 | 4.454102E+01 | -5.099365E+00 | 3.377734E+01 |
| 5.262400E+09 | -9.657227E+00 | 4.139062E+01 | -5.469727E+00 | 1.859570E+01 |
| 5.311750E+09 | -8.983887E+00 | 3.774023E+01 | -5.854004E+00 | 3.698242E+00 |
| 5.361100E+09 | -8.165527E+00 | 3.329297E+01 | -6.256348E+00 | -1.097412E+01 |
| 5.410450E+09 | -7.257568E+00 | 2.737793E+01 | -6.627686E+00 | -2.536426E+01 |
| 5.459800E+09 | -6.394775E+00 | 1.940430E+01 | -6.981201E+00 | -3.917187E+01 |
| 5.509150E+09 | -5.698242E+00 | 9.921875E+00 | -7.299072E+00 | -5.274804E+01 |
| 5.558500E+09 | -5.230225E+00 | -2.828979E-01 | -7.535400E+00 | -6.598437E+01 |
| 5.607850E+09 | -4.923828E+00 | -1.108154E+01 | -7.714111E+00 | -7.903125E+01 |
| 5.657200E+09 | -4.776611E+00 | -2.192773E+01 | -7.810059E+00 | -9.195704E+01 |
| 5.706550E+09 | -4.788330E+00 | -3.311718E+01 | -7.815430E+00 | -1.049375E+02 |
| 5.755900E+09 | -4.925049E+00 | -4.452538E+01 | -7.742920E+00 | -1.179219E+02 |
| 5.805250E+09 | -5.171387E+00 | -5.625586E+01 | -7.611328E+00 | -1.309219E+02 |
| 5.854600E+09 | -5.541016E+00 | -6.829687E+01 | -7.428467E+00 | -1.443438E+02 |
| 5.903950E+09 | -6.040527E+00 | -8.080858E+01 | -7.181396E+00 | -1.579375E+02 |
| 5.953300E+09 | -6.662354E+00 | -9.390625E+01 | -6.923096E+00 | -1.717578E+02 |
| 6.002650E+09 | -7.371826E+00 | -1.075195E+02 | -6.642090E+00 | 1.738594E+02 |
| 6.052000E+09 | -8.180664E+00 | -1.220820E+02 | -6.347412E+00 | 1.593594E+02 |
| 6.101350E+09 | -9.012695E+00 | -1.374844E+02 | -6.077637E+00 | 1.445781E+02 |
| 6.150700E+09 | -9.846680E+00 | -1.536875E+02 | -5.821045E+00 | 1.295234E+02 |
| 6.200050E+09 | -1.059375E+01 | -1.709297E+02 | -5.586426E+00 | 1.143672E+02 |
| 6.249400E+09 | -1.125586E+01 | 1.713125E+02 | -5.400879E+00 | 9.923437E+01 |
| 6.298750E+09 | -1.178809E+01 | 1.530234E+02 | -5.250244E+00 | 8.400000E+01 |
| 6.348100E+09 | -1.217383E+01 | 1.346250E+02 | -5.120361E+00 | 6.881249E+01 |
| 6.397450E+09 | -1.245313E+01 | 1.162070E+02 | -5.018066E+00 | 5.369531E+01 |
| 6.446800E+09 | -1.257666E+01 | 9.789843E+01 | -4.945068E+00 | 3.876367E+01 |
| 6.496150E+09 | -1.258594E+01 | 8.007813E+01 | -4.891846E+00 | 2.387598E+01 |
| 6.545500E+09 | -1.252197E+01 | 6.270702E+01 | -4.833252E+00 | 9.174805E+00 |
| 6.594850E+09 | -1.240088E+01 | 4.639648E+01 | -4.789795E+00 | -5.457520E+00 |
| 6.644200E+09 | -1.229834E+01 | 3.107129E+01 | -4.746582E+00 | -1.998828E+01 |
| 6.693550E+09 | -1.226514E+01 | 1.723437E+01 | -4.701660E+00 | -3.447070E+01 |

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|---|---|---|---|---|
| 6.742900E+09 | -1.243115E+01 | 5.401123E+00 | -4.663330E+00 | -4.897461E+01 |
| 6.792250E+09 | -1.269971E+01 | -4.295654E+00 | -4.614258E+00 | -6.352734E+01 |
| 6.841600E+09 | -1.300635E+01 | -1.100293E+01 | -4.580078E+00 | -7.806641E+01 |
| 6.890950E+09 | -1.325684E+01 | -1.566650E+01 | -4.547852E+00 | -9.285547E+01 |
| 6.940300E+09 | -1.332568E+01 | -1.927832E+01 | -4.528320E+00 | -1.075039E+02 |
| 6.989650E+09 | -1.329688E+01 | -2.186035E+01 | -4.524658E+00 | -1.224336E+02 |
| 7.039000E+09 | -1.317578E+01 | -2.420996E+01 | -4.542969E+00 | -1.373437E+02 |
| 7.088350E+09 | -1.294873E+01 | -2.623828E+01 | -4.591064E+00 | -1.523828E+02 |
| 7.137700E+09 | -1.263184E+01 | -2.821582E+01 | -4.658447E+00 | -1.672500E+02 |
| 7.187050E+09 | -1.222656E+01 | -3.017969E+01 | -4.765137E+00 | 1.777109E+02 |
| 7.236400E+09 | -1.172656E+01 | -3.257421E+01 | -4.847168E+00 | 1.626562E+02 |
| 7.285750E+09 | -1.110986E+01 | -3.570703E+01 | -4.957031E+00 | 1.479766E+02 |
| 7.335100E+09 | -1.046680E+01 | -3.978711E+01 | -5.110107E+00 | 1.329922E+02 |
| 7.384450E+09 | -9.962402E+00 | -4.556250E+01 | -5.197998E+00 | 1.180195E+02 |
| 7.433800E+09 | -9.633301E+00 | -5.195313E+01 | -5.331787E+00 | 1.032109E+02 |
| 7.483150E+09 | -9.523438E+00 | -5.754101E+01 | -5.465820E+00 | 8.803514E+01 |
| 7.532500E+09 | -9.521484E+00 | -6.242382E+01 | -5.574707E+00 | 7.281640E+01 |
| 7.581850E+09 | -9.478516E+00 | -6.632030E+01 | -5.715332E+00 | 5.759570E+01 |
| 7.631200E+09 | -9.398926E+00 | -6.973437E+01 | -5.895264E+00 | 4.219140E+01 |
| 7.680550E+09 | -9.257324E+00 | -7.300781E+01 | -6.092529E+00 | 2.642187E+01 |
| 7.729900E+09 | -9.044434E+00 | -7.607812E+01 | -6.274170E+00 | 1.085840E+01 |
| 7.779250E+09 | -8.795898E+00 | -7.916406E+01 | -6.601563E+00 | -4.294434E+00 |
| 7.828600E+09 | -8.461914E+00 | -8.237108E+01 | -6.928223E+00 | -2.048047E+01 |
| 7.877950E+09 | -8.063965E+00 | -8.591015E+01 | -7.195557E+00 | -3.533984E+01 |
| 7.927300E+09 | -7.552490E+00 | -9.001953E+01 | -7.607666E+00 | -5.051171E+01 |
| 7.976650E+09 | -7.003662E+00 | -9.503515E+01 | -7.972168E+00 | -6.524609E+01 |
| 8.026000E+09 | -6.450684E+00 | -1.016484E+02 | -8.325195E+00 | -7.955078E+01 |
| 8.075350E+09 | -5.957764E+00 | -1.095898E+02 | -8.682129E+00 | -9.335155E+01 |
| 8.124700E+09 | -5.662842E+00 | -1.186601E+02 | -8.977539E+00 | -1.072344E+02 |
| 8.174050E+09 | -5.552246E+00 | -1.285859E+02 | -9.197266E+00 | -1.204922E+02 |
| 8.223400E+09 | -5.624268E+00 | -1.388672E+02 | -9.351074E+00 | -1.338906E+02 |
| 8.272750E+09 | -5.916748E+00 | -1.497344E+02 | -9.440918E+00 | -1.471641E+02 |
| 8.322100E+09 | -6.369629E+00 | -1.610000E+02 | -9.420898E+00 | -1.611484E+02 |
| 8.371450E+09 | -7.057129E+00 | -1.730156E+02 | -9.328125E+00 | -1.744688E+02 |
| 8.420800E+09 | -7.938232E+00 | 1.737734E+02 | -9.260254E+00 | 1.708047E+02 |
| 8.470150E+09 | -9.075195E+00 | 1.590859E+02 | -9.073730E+00 | 1.561719E+02 |
| 8.519500E+09 | -1.020117E+01 | 1.413125E+02 | -8.903809E+00 | 1.408594E+02 |
| 8.568850E+09 | -1.124219E+01 | 1.215859E+02 | -8.742188E+00 | 1.250625E+02 |
| 8.618200E+09 | -1.203320E+01 | 1.003633E+02 | -8.619629E+00 | 1.087148E+02 |
| 8.667550E+09 | -1.259473E+01 | 7.867188E+01 | -8.506348E+00 | 9.202734E+01 |
| 8.716900E+09 | -1.295752E+01 | 5.640234E+01 | -8.449707E+00 | 7.507421E+01 |
| 8.766250E+09 | -1.309766E+01 | 3.407227E+01 | -8.456543E+00 | 5.809570E+01 |
| 8.815600E+09 | -1.306787E+01 | 1.192822E+01 | -8.540527E+00 | 4.101563E+01 |
| 8.864950E+09 | -1.283057E+01 | -9.937500E+00 | -8.616211E+00 | 2.415136E+01 |
| 8.914300E+09 | -1.237354E+01 | -3.100293E+01 | -8.770508E+00 | 7.477539E+00 |
| 8.963650E+09 | -1.171533E+01 | -5.103320E+01 | -8.911621E+00 | -8.984375E+00 |
| 9.013000E+09 | -1.080664E+01 | -6.926562E+01 | -9.070801E+00 | -2.487207E+01 |
| 9.062350E+09 | -9.943359E+00 | -8.442577E+01 | -9.206055E+00 | -4.089844E+01 |
| 9.111700E+09 | -9.145508E+00 | -9.719921E+01 | -9.331055E+00 | -5.645508E+01 |

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|---|---|---|---|---|
| 9.161050E+09 | -8.638184E+00 | -1.077422E+02 | -9.376953E+00 | -7.193749E+01 |
| 9.210400E+09 | -8.376953E+00 | -1.172070E+02 | -9.439453E+00 | -8.703516E+01 |
| 9.259750E+09 | -8.262695E+00 | -1.247422E+02 | -9.437500E+00 | -1.025742E+02 |
| 9.309100E+09 | -8.297852E+00 | -1.309062E+02 | -9.411621E+00 | -1.178945E+02 |
| 9.358450E+09 | -8.290527E+00 | -1.359766E+02 | -9.349121E+00 | -1.335391E+02 |
| 9.407800E+09 | -8.288086E+00 | -1.399922E+02 | -9.342773E+00 | -1.491406E+02 |
| 9.457150E+09 | -8.262207E+00 | -1.436875E+02 | -9.277344E+00 | -1.652500E+02 |
| 9.506500E+09 | -8.173340E+00 | -1.468437E+02 | -9.264160E+00 | 1.790313E+02 |
| 9.555850E+09 | -8.079102E+00 | -1.498437E+02 | -9.250488E+00 | 1.629453E+02 |
| 9.605200E+09 | -7.921631E+00 | -1.526641E+02 | -9.303711E+00 | 1.472422E+02 |
| 9.654550E+09 | -7.764404E+00 | -1.553516E+02 | -9.319824E+00 | 1.314141E+02 |
| 9.703900E+09 | -7.580322E+00 | -1.585312E+02 | -9.404297E+00 | 1.157383E+02 |
| 9.753250E+09 | -7.334229E+00 | -1.616328E+02 | -9.457520E+00 | 1.000742E+02 |
| 9.802600E+09 | -7.070557E+00 | -1.649453E+02 | -9.533691E+00 | 8.610546E+01 |
| 9.851950E+09 | -6.802979E+00 | -1.685156E+02 | -9.597656E+00 | 7.362109E+01 |
| 9.901300E+09 | -6.621338E+00 | -1.721016E+02 | -9.677246E+00 | 6.268749E+01 |
| 9.950650E+09 | -6.513428E+00 | -1.757422E+02 | -9.701172E+00 | 5.317577E+01 |
| 1.000000E+10 | -6.460938E+00 | -1.788594E+02 | -9.748535E+00 | 4.530078E+01 |

## A.11. 130-mil wide N-shaped structure with 0.5S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -2.216601E+01 | -1.345078E+02 | -8.332443E-02 | -3.400000E+01 |
| 1.793500E+08 | -2.139453E+01 | -1.399062E+02 | -9.954071E-02 | -3.862695E+01 |
| 2.287000E+08 | -2.057227E+01 | -1.462109E+02 | -1.168556E-01 | -4.402539E+01 |
| 2.780500E+08 | -1.972558E+01 | -1.533906E+02 | -1.389542E-01 | -5.019336E+01 |
| 3.274000E+08 | -1.885058E+01 | -1.615078E+02 | -1.601257E-01 | -5.712500E+01 |
| 3.767500E+08 | -1.795996E+01 | -1.705547E+02 | -1.858521E-01 | -6.483593E+01 |
| 4.261000E+08 | -1.707422E+01 | 1.794922E+02 | -2.134094E-01 | -7.330859E+01 |
| 4.754500E+08 | -1.643847E+01 | 1.695625E+02 | -2.363281E-01 | -8.178125E+01 |
| 5.248000E+08 | -1.600098E+01 | 1.595859E+02 | -2.595367E-01 | -9.024218E+01 |
| 5.741500E+08 | -1.571729E+01 | 1.495469E+02 | -2.790985E-01 | -9.876953E+01 |
| 6.235000E+08 | -1.556396E+01 | 1.395937E+02 | -2.984772E-01 | -1.072969E+02 |
| 6.728500E+08 | -1.554199E+01 | 1.295000E+02 | -3.114777E-01 | -1.158672E+02 |
| 7.222000E+08 | -1.564697E+01 | 1.194102E+02 | -3.172760E-01 | -1.244609E+02 |
| 7.715500E+08 | -1.589697E+01 | 1.092812E+02 | -3.243408E-01 | -1.331328E+02 |
| 8.209000E+08 | -1.627832E+01 | 9.919140E+01 | -3.267365E-01 | -1.418437E+02 |
| 8.702500E+08 | -1.684082E+01 | 8.917187E+01 | -3.292084E-01 | -1.506406E+02 |
| 9.196000E+08 | -1.758105E+01 | 7.930859E+01 | -3.309631E-01 | -1.595078E+02 |
| 9.689500E+08 | -1.857324E+01 | 6.986718E+01 | -3.296661E-01 | -1.684609E+02 |
| 1.018300E+09 | -1.990625E+01 | 6.100390E+01 | -3.383026E-01 | -1.774765E+02 |
| 1.067650E+09 | -2.166504E+01 | 5.425586E+01 | -3.391418E-01 | 1.733594E+02 |
| 1.117000E+09 | -2.345801E+01 | 5.386132E+01 | -3.411560E-01 | 1.641953E+02 |
| 1.166350E+09 | -2.486133E+01 | 5.630859E+01 | -3.494720E-01 | 1.548750E+02 |
| 1.215700E+09 | -2.584473E+01 | 5.936523E+01 | -3.629761E-01 | 1.454766E+02 |
| 1.265050E+09 | -2.653418E+01 | 6.318749E+01 | -3.736725E-01 | 1.359297E+02 |
| 1.314400E+09 | -2.702148E+01 | 6.719140E+01 | -3.867645E-01 | 1.263789E+02 |

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|---|---|---|---|---|
| 1.363750E+09 | -2.727344E+01 | 7.106640E+01 | -4.036255E-01 | 1.167148E+02 |
| 1.413100E+09 | -2.725390E+01 | 7.529687E+01 | -4.244843E-01 | 1.069961E+02 |
| 1.462450E+09 | -2.702832E+01 | 7.911718E+01 | -4.400940E-01 | 9.719530E+01 |
| 1.511800E+09 | -2.649219E+01 | 8.246874E+01 | -4.611359E-01 | 8.727343E+01 |
| 1.561150E+09 | -2.558594E+01 | 8.521484E+01 | -4.784088E-01 | 7.724999E+01 |
| 1.610500E+09 | -2.420703E+01 | 8.562109E+01 | -5.058899E-01 | 6.721484E+01 |
| 1.659850E+09 | -2.274609E+01 | 7.960546E+01 | -5.369263E-01 | 5.701172E+01 |
| 1.709200E+09 | -2.162793E+01 | 7.050781E+01 | -5.643616E-01 | 4.679883E+01 |
| 1.758550E+09 | -2.086035E+01 | 6.068945E+01 | -5.940247E-01 | 3.649805E+01 |
| 1.807900E+09 | -2.026953E+01 | 4.980469E+01 | -6.277771E-01 | 2.618555E+01 |
| 1.857250E+09 | -1.974121E+01 | 3.853125E+01 | -6.719666E-01 | 1.567871E+01 |
| 1.906600E+09 | -1.930957E+01 | 2.661230E+01 | -7.185059E-01 | 5.163574E+00 |
| 1.955950E+09 | -1.890723E+01 | 1.381494E+01 | -7.722168E-01 | -5.437012E+00 |
| 2.005300E+09 | -1.854785E+01 | 2.719116E-01 | -8.461609E-01 | -1.597314E+01 |
| 2.054650E+09 | -1.831347E+01 | -1.375928E+01 | -9.063416E-01 | -2.645996E+01 |
| 2.104000E+09 | -1.815137E+01 | -2.632910E+01 | -9.512939E-01 | -3.692578E+01 |
| 2.153350E+09 | -1.778516E+01 | -3.870898E+01 | -9.796753E-01 | -4.747070E+01 |
| 2.202700E+09 | -1.728223E+01 | -5.132421E+01 | -1.019287E+00 | -5.806054E+01 |
| 2.252050E+09 | -1.670312E+01 | -6.405078E+01 | -1.045166E+00 | -6.878515E+01 |
| 2.301400E+09 | -1.604199E+01 | -7.689453E+01 | -1.081299E+00 | -7.941015E+01 |
| 2.350750E+09 | -1.534717E+01 | -8.964062E+01 | -1.133118E+00 | -9.008984E+01 |
| 2.400100E+09 | -1.462305E+01 | -1.023281E+02 | -1.172668E+00 | -1.007500E+02 |
| 2.449450E+09 | -1.386377E+01 | -1.145039E+02 | -1.214050E+00 | -1.113789E+02 |
| 2.498800E+09 | -1.313086E+01 | -1.263515E+02 | -1.274475E+00 | -1.219531E+02 |
| 2.548150E+09 | -1.234424E+01 | -1.373125E+02 | -1.312012E+00 | -1.325625E+02 |
| 2.597500E+09 | -1.143555E+01 | -1.478359E+02 | -1.398865E+00 | -1.432344E+02 |
| 2.646850E+09 | -1.044043E+01 | -1.598750E+02 | -1.466736E+00 | -1.539063E+02 |
| 2.696200E+09 | -9.633789E+00 | -1.719297E+02 | -1.603577E+00 | -1.641797E+02 |
| 2.745550E+09 | -8.947266E+00 | 1.762656E+02 | -1.728333E+00 | -1.746172E+02 |
| 2.794900E+09 | -8.323242E+00 | 1.647656E+02 | -1.855774E+00 | 1.755625E+02 |
| 2.844250E+09 | -7.773682E+00 | 1.536094E+02 | -2.014282E+00 | 1.655859E+02 |
| 2.893600E+09 | -7.287354E+00 | 1.426250E+02 | -2.153198E+00 | 1.559609E+02 |
| 2.942950E+09 | -6.863281E+00 | 1.318984E+02 | -2.312134E+00 | 1.464531E+02 |
| 2.992300E+09 | -6.503662E+00 | 1.213750E+02 | -2.454834E+00 | 1.371797E+02 |
| 3.041650E+09 | -6.195313E+00 | 1.110703E+02 | -2.597046E+00 | 1.281953E+02 |
| 3.091000E+09 | -5.940674E+00 | 1.009883E+02 | -2.759521E+00 | 1.194141E+02 |
| 3.140350E+09 | -5.733154E+00 | 9.103516E+01 | -2.845459E+00 | 1.107227E+02 |
| 3.189700E+09 | -5.563477E+00 | 8.126171E+01 | -2.955200E+00 | 1.026367E+02 |
| 3.239050E+09 | -5.442871E+00 | 7.160546E+01 | -3.048096E+00 | 9.417187E+01 |
| 3.288400E+09 | -5.360107E+00 | 6.214844E+01 | -3.083252E+00 | 8.620703E+01 |
| 3.337750E+09 | -5.315186E+00 | 5.275195E+01 | -3.128174E+00 | 7.800781E+01 |
| 3.387100E+09 | -5.311035E+00 | 4.337304E+01 | -3.111328E+00 | 7.028125E+01 |
| 3.436450E+09 | -5.343506E+00 | 3.409765E+01 | -3.131226E+00 | 6.227148E+01 |
| 3.485800E+09 | -5.406738E+00 | 2.476953E+01 | -3.052612E+00 | 5.439258E+01 |
| 3.535150E+09 | -5.509277E+00 | 1.543164E+01 | -2.995850E+00 | 4.658789E+01 |
| 3.584500E+09 | -5.666992E+00 | 6.284180E+00 | -2.919434E+00 | 3.849023E+01 |
| 3.633850E+09 | -5.826660E+00 | -2.947144E+00 | -2.801025E+00 | 3.035351E+01 |
| 3.683200E+09 | -6.029053E+00 | -1.227734E+01 | -2.698975E+00 | 2.246777E+01 |
| 3.732550E+09 | -6.269775E+00 | -2.172363E+01 | -2.614746E+00 | 1.411035E+01 |

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|---|---|---|---|---|
| 3.781900E+09 | -6.537354E+00 | -3.116211E+01 | -2.470947E+00 | 5.769043E+00 |
| 3.831250E+09 | -6.832031E+00 | -4.081836E+01 | -2.361084E+00 | -2.543335E+00 |
| 3.880600E+09 | -7.155029E+00 | -5.062304E+01 | -2.255981E+00 | -1.100732E+01 |
| 3.929950E+09 | -7.504150E+00 | -6.046875E+01 | -2.169067E+00 | -1.978808E+01 |
| 3.979300E+09 | -7.872559E+00 | -7.061328E+01 | -2.035034E+00 | -2.846191E+01 |
| 4.028650E+09 | -8.252930E+00 | -8.080858E+01 | -1.982056E+00 | -3.709179E+01 |
| 4.078000E+09 | -8.640137E+00 | -9.112499E+01 | -1.928345E+00 | -4.596289E+01 |
| 4.127350E+09 | -8.991699E+00 | -1.018516E+02 | -1.854431E+00 | -5.478516E+01 |
| 4.176700E+09 | -9.367676E+00 | -1.126914E+02 | -1.803833E+00 | -6.359179E+01 |
| 4.226050E+09 | -9.706055E+00 | -1.236601E+02 | -1.777893E+00 | -7.258984E+01 |
| 4.275400E+09 | -1.001318E+01 | -1.346719E+02 | -1.747681E+00 | -8.163671E+01 |
| 4.324750E+09 | -1.029346E+01 | -1.459219E+02 | -1.726929E+00 | -9.061327E+01 |
| 4.374100E+09 | -1.052881E+01 | -1.572656E+02 | -1.727112E+00 | -9.964844E+01 |
| 4.423450E+09 | -1.071729E+01 | -1.686641E+02 | -1.740356E+00 | -1.086953E+02 |
| 4.472800E+09 | -1.086084E+01 | 1.798906E+02 | -1.746826E+00 | -1.177812E+02 |
| 4.522150E+09 | -1.096484E+01 | 1.685859E+02 | -1.772217E+00 | -1.268750E+02 |
| 4.571500E+09 | -1.102490E+01 | 1.572578E+02 | -1.794861E+00 | -1.360703E+02 |
| 4.620850E+09 | -1.103564E+01 | 1.460781E+02 | -1.810852E+00 | -1.453359E+02 |
| 4.670200E+09 | -1.104150E+01 | 1.348906E+02 | -1.844360E+00 | -1.546172E+02 |
| 4.719550E+09 | -1.102686E+01 | 1.237695E+02 | -1.886963E+00 | -1.640703E+02 |
| 4.768900E+09 | -1.104150E+01 | 1.129297E+02 | -1.928711E+00 | -1.735859E+02 |
| 4.818250E+09 | -1.109180E+01 | 1.021016E+02 | -1.973877E+00 | 1.767812E+02 |
| 4.867600E+09 | -1.119043E+01 | 9.174999E+01 | -2.032715E+00 | 1.670703E+02 |
| 4.916950E+09 | -1.138672E+01 | 8.176561E+01 | -2.099976E+00 | 1.570937E+02 |
| 4.966300E+09 | -1.167773E+01 | 7.231250E+01 | -2.157471E+00 | 1.469844E+02 |
| 5.015650E+09 | -1.211523E+01 | 6.401953E+01 | -2.227783E+00 | 1.367188E+02 |
| 5.065000E+09 | -1.270459E+01 | 5.747070E+01 | -2.310425E+00 | 1.261797E+02 |
| 5.114350E+09 | -1.323242E+01 | 5.326953E+01 | -2.416626E+00 | 1.152656E+02 |
| 5.163700E+09 | -1.356348E+01 | 5.082031E+01 | -2.550293E+00 | 1.041172E+02 |
| 5.213050E+09 | -1.366260E+01 | 4.924999E+01 | -2.727051E+00 | 9.279688E+01 |
| 5.262400E+09 | -1.358936E+01 | 4.811523E+01 | -2.923096E+00 | 8.126562E+01 |
| 5.311750E+09 | -1.333838E+01 | 4.711914E+01 | -3.157471E+00 | 6.939453E+01 |
| 5.361100E+09 | -1.293213E+01 | 4.619336E+01 | -3.456543E+00 | 5.729882E+01 |
| 5.410450E+09 | -1.239648E+01 | 4.507617E+01 | -3.799316E+00 | 4.528516E+01 |
| 5.459800E+09 | -1.168848E+01 | 4.395312E+01 | -4.200439E+00 | 3.325000E+01 |
| 5.509150E+09 | -1.082324E+01 | 4.241211E+01 | -4.619385E+00 | 2.112500E+01 |
| 5.558500E+09 | -9.761230E+00 | 3.978125E+01 | -5.067139E+00 | 9.083984E+00 |
| 5.607850E+09 | -8.503906E+00 | 3.551562E+01 | -5.560791E+00 | -2.930664E+00 |
| 5.657200E+09 | -7.301025E+00 | 2.898730E+01 | -6.085449E+00 | -1.473145E+01 |
| 5.706550E+09 | -6.290283E+00 | 2.069824E+01 | -6.600098E+00 | -2.630957E+01 |
| 5.755900E+09 | -5.502930E+00 | 1.177979E+01 | -7.094971E+00 | -3.759961E+01 |
| 5.805250E+09 | -4.887207E+00 | 2.672363E+00 | -7.602295E+00 | -4.852148E+01 |
| 5.854600E+09 | -4.391602E+00 | -6.414795E+00 | -8.060547E+00 | -5.933788E+01 |
| 5.903950E+09 | -3.989868E+00 | -1.542236E+01 | -8.429688E+00 | -6.982812E+01 |
| 5.953300E+09 | -3.645264E+00 | -2.448633E+01 | -8.777832E+00 | -8.021875E+01 |
| 6.002650E+09 | -3.378296E+00 | -3.365820E+01 | -9.045898E+00 | -9.066797E+01 |
| 6.052000E+09 | -3.195068E+00 | -4.281836E+01 | -9.259766E+00 | -1.008828E+02 |
| 6.101350E+09 | -3.068115E+00 | -5.196289E+01 | -9.442871E+00 | -1.109453E+02 |
| 6.150700E+09 | -2.993774E+00 | -6.103320E+01 | -9.532227E+00 | -1.208359E+02 |

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|---|---|---|---|---|
| 6.200050E+09 | -2.957764E+00 | -7.018749E+01 | -9.564453E+00 | -1.306406E+02 |
| 6.249400E+09 | -2.942627E+00 | -7.934375E+01 | -9.519043E+00 | -1.405391E+02 |
| 6.298750E+09 | -2.949829E+00 | -8.867188E+01 | -9.433594E+00 | -1.502812E+02 |
| 6.348100E+09 | -2.977051E+00 | -9.825390E+01 | -9.289063E+00 | -1.605703E+02 |
| 6.397450E+09 | -3.050293E+00 | -1.081914E+02 | -9.098633E+00 | -1.704219E+02 |
| 6.446800E+09 | -3.166992E+00 | -1.183945E+02 | -8.905273E+00 | 1.796094E+02 |
| 6.496150E+09 | -3.321899E+00 | -1.288359E+02 | -8.673340E+00 | 1.695547E+02 |
| 6.545500E+09 | -3.518066E+00 | -1.396016E+02 | -8.432617E+00 | 1.594844E+02 |
| 6.594850E+09 | -3.716675E+00 | -1.506484E+02 | -8.177246E+00 | 1.495469E+02 |
| 6.644200E+09 | -3.948730E+00 | -1.620547E+02 | -7.909668E+00 | 1.393906E+02 |
| 6.693550E+09 | -4.187744E+00 | -1.738828E+02 | -7.656250E+00 | 1.292813E+02 |
| 6.742900E+09 | -4.435303E+00 | 1.740234E+02 | -7.372070E+00 | 1.190625E+02 |
| 6.792250E+09 | -4.683350E+00 | 1.614609E+02 | -7.130127E+00 | 1.090781E+02 |
| 6.841600E+09 | -4.917480E+00 | 1.486719E+02 | -6.890625E+00 | 9.861717E+01 |
| 6.890950E+09 | -5.138184E+00 | 1.355234E+02 | -6.643066E+00 | 8.866014E+01 |
| 6.940300E+09 | -5.338379E+00 | 1.221719E+02 | -6.480957E+00 | 7.836719E+01 |
| 6.989650E+09 | -5.511719E+00 | 1.087617E+02 | -6.306885E+00 | 6.814453E+01 |
| 7.039000E+09 | -5.641357E+00 | 9.540234E+01 | -6.142334E+00 | 5.795116E+01 |
| 7.088350E+09 | -5.712646E+00 | 8.214453E+01 | -5.996582E+00 | 4.794531E+01 |
| 7.137700E+09 | -5.743896E+00 | 6.893749E+01 | -5.921631E+00 | 3.780078E+01 |
| 7.187050E+09 | -5.718262E+00 | 5.595312E+01 | -5.841309E+00 | 2.764551E+01 |
| 7.236400E+09 | -5.657959E+00 | 4.327344E+01 | -5.734375E+00 | 1.766602E+01 |
| 7.285750E+09 | -5.557373E+00 | 3.081055E+01 | -5.750244E+00 | 8.108887E+00 |
| 7.335100E+09 | -5.442139E+00 | 1.888379E+01 | -5.779785E+00 | -2.293457E+00 |
| 7.384450E+09 | -5.315186E+00 | 7.263184E+00 | -5.749268E+00 | -1.187109E+01 |
| 7.433800E+09 | -5.176758E+00 | -3.780762E+00 | -5.854736E+00 | -2.135352E+01 |
| 7.483150E+09 | -5.035889E+00 | -1.433887E+01 | -5.932129E+00 | -3.093750E+01 |
| 7.532500E+09 | -4.895996E+00 | -2.454297E+01 | -6.007080E+00 | -4.046484E+01 |
| 7.581850E+09 | -4.775146E+00 | -3.441797E+01 | -6.098633E+00 | -4.941406E+01 |
| 7.631200E+09 | -4.691895E+00 | -4.401563E+01 | -6.235352E+00 | -5.838476E+01 |
| 7.680550E+09 | -4.638672E+00 | -5.312695E+01 | -6.342041E+00 | -6.739452E+01 |
| 7.729900E+09 | -4.635010E+00 | -6.192187E+01 | -6.407959E+00 | -7.603516E+01 |
| 7.779250E+09 | -4.684570E+00 | -7.046875E+01 | -6.575195E+00 | -8.437891E+01 |
| 7.828600E+09 | -4.797852E+00 | -7.858203E+01 | -6.638184E+00 | -9.369141E+01 |
| 7.877950E+09 | -4.970215E+00 | -8.648829E+01 | -6.625244E+00 | -1.016680E+02 |
| 7.927300E+09 | -5.225098E+00 | -9.384375E+01 | -6.721191E+00 | -1.107031E+02 |
| 7.976650E+09 | -5.577148E+00 | -1.007031E+02 | -6.679199E+00 | -1.198398E+02 |
| 8.026000E+09 | -6.010254E+00 | -1.066602E+02 | -6.633545E+00 | -1.290703E+02 |
| 8.075350E+09 | -6.485107E+00 | -1.113008E+02 | -6.633789E+00 | -1.386172E+02 |
| 8.124700E+09 | -6.924316E+00 | -1.147148E+02 | -6.641357E+00 | -1.492344E+02 |
| 8.174050E+09 | -7.242432E+00 | -1.171289E+02 | -6.687988E+00 | -1.600391E+02 |
| 8.223400E+09 | -7.446045E+00 | -1.190586E+02 | -6.745117E+00 | -1.713984E+02 |
| 8.272750E+09 | -7.515869E+00 | -1.207422E+02 | -6.976807E+00 | 1.770859E+02 |
| 8.322100E+09 | -7.473877E+00 | -1.222852E+02 | -7.198975E+00 | 1.645469E+02 |
| 8.371450E+09 | -7.337402E+00 | -1.240351E+02 | -7.581787E+00 | 1.529297E+02 |
| 8.420800E+09 | -7.099365E+00 | -1.258906E+02 | -8.031250E+00 | 1.400469E+02 |
| 8.470150E+09 | -6.760498E+00 | -1.280781E+02 | -8.575684E+00 | 1.282344E+02 |
| 8.519500E+09 | -6.309082E+00 | -1.308047E+02 | -9.230469E+00 | 1.156914E+02 |
| 8.568850E+09 | -5.768799E+00 | -1.344453E+02 | -9.959473E+00 | 1.034687E+02 |

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|---|---|---|---|---|
| 8.618200E+09 | -5.186523E+00 | -1.394766E+02 | -1.069922E+01 | 9.167187E+01 |
| 8.667550E+09 | -4.633545E+00 | -1.457891E+02 | -1.158789E+01 | 8.014452E+01 |
| 8.716900E+09 | -4.208740E+00 | -1.530937E+02 | -1.234424E+01 | 6.816406E+01 |
| 8.766250E+09 | -3.900513E+00 | -1.612578E+02 | -1.319727E+01 | 5.698828E+01 |
| 8.815600E+09 | -3.717651E+00 | -1.697891E+02 | -1.392969E+01 | 4.516211E+01 |
| 8.864950E+09 | -3.649902E+00 | -1.788516E+02 | -1.466943E+01 | 3.345508E+01 |
| 8.914300E+09 | -3.658203E+00 | 1.718047E+02 | -1.521680E+01 | 2.079688E+01 |
| 8.963650E+09 | -3.755127E+00 | 1.619688E+02 | -1.581445E+01 | 8.449707E+00 |
| 9.013000E+09 | -3.928833E+00 | 1.515312E+02 | -1.623340E+01 | -5.590820E+00 |
| 9.062350E+09 | -4.178955E+00 | 1.403906E+02 | -1.656543E+01 | -1.928418E+01 |
| 9.111700E+09 | -4.495605E+00 | 1.282344E+02 | -1.677246E+01 | -3.371484E+01 |
| 9.161050E+09 | -4.844727E+00 | 1.152187E+02 | -1.696289E+01 | -4.876953E+01 |
| 9.210400E+09 | -5.238525E+00 | 1.008789E+02 | -1.693164E+01 | -6.442187E+01 |
| 9.259750E+09 | -5.606689E+00 | 8.528906E+01 | -1.692480E+01 | -7.953906E+01 |
| 9.309100E+09 | -5.945557E+00 | 6.868750E+01 | -1.679199E+01 | -9.549219E+01 |
| 9.358450E+09 | -6.199463E+00 | 5.117578E+01 | -1.666113E+01 | -1.108867E+02 |
| 9.407800E+09 | -6.377197E+00 | 3.314648E+01 | -1.647656E+01 | -1.264258E+02 |
| 9.457150E+09 | -6.466553E+00 | 1.464063E+01 | -1.628418E+01 | -1.410859E+02 |
| 9.506500E+09 | -6.465088E+00 | -3.780762E+00 | -1.608984E+01 | -1.555781E+02 |
| 9.555850E+09 | -6.375000E+00 | -2.212793E+01 | -1.590479E+01 | -1.687891E+02 |
| 9.605200E+09 | -6.188477E+00 | -3.994922E+01 | -1.576318E+01 | 1.781953E+02 |
| 9.654550E+09 | -5.916016E+00 | -5.688086E+01 | -1.562891E+01 | 1.662422E+02 |
| 9.703900E+09 | -5.588379E+00 | -7.290625E+01 | -1.551563E+01 | 1.547969E+02 |
| 9.753250E+09 | -5.205566E+00 | -8.751562E+01 | -1.542871E+01 | 1.444844E+02 |
| 9.802600E+09 | -4.829102E+00 | -1.000703E+02 | -1.536621E+01 | 1.352031E+02 |
| 9.851950E+09 | -4.473389E+00 | -1.106328E+02 | -1.532080E+01 | 1.273945E+02 |
| 9.901300E+09 | -4.180176E+00 | -1.194531E+02 | -1.527686E+01 | 1.205273E+02 |
| 9.950650E+09 | -3.928589E+00 | -1.266562E+02 | -1.522949E+01 | 1.151211E+02 |
| 1.000000E+10 | -3.735229E+00 | -1.323359E+02 | -1.523340E+01 | 1.104140E+02 |

## A.12. 130-mil wide M-shaped structure with 0.5S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -1.967578E+01 | -1.417422E+02 | -1.389542E-01 | -4.216016E+01 |
| 1.793500E+08 | -1.901953E+01 | -1.482109E+02 | -1.614151E-01 | -4.786523E+01 |
| 2.287000E+08 | -1.834180E+01 | -1.557656E+02 | -1.853027E-01 | -5.452538E+01 |
| 2.780500E+08 | -1.766894E+01 | -1.643750E+02 | -2.092285E-01 | -6.213476E+01 |
| 3.274000E+08 | -1.701465E+01 | -1.741016E+02 | -2.332535E-01 | -7.071094E+01 |
| 3.767500E+08 | -1.638769E+01 | 1.750469E+02 | -2.573242E-01 | -8.024609E+01 |
| 4.261000E+08 | -1.581689E+01 | 1.631016E+02 | -2.845612E-01 | -9.075390E+01 |
| 4.754500E+08 | -1.553809E+01 | 1.511328E+02 | -3.063354E-01 | -1.013047E+02 |
| 5.248000E+08 | -1.552734E+01 | 1.392031E+02 | -3.212738E-01 | -1.118633E+02 |
| 5.741500E+08 | -1.575342E+01 | 1.271250E+02 | -3.362885E-01 | -1.225039E+02 |
| 6.235000E+08 | -1.625195E+01 | 1.150430E+02 | -3.433533E-01 | -1.332266E+02 |
| 6.728500E+08 | -1.705469E+01 | 1.030000E+02 | -3.477631E-01 | -1.440312E+02 |
| 7.222000E+08 | -1.833105E+01 | 9.126562E+01 | -3.538361E-01 | -1.549375E+02 |
| 7.715500E+08 | -2.052832E+01 | 8.139063E+01 | -3.570557E-01 | -1.659141E+02 |
| 8.209000E+08 | -2.245703E+01 | 8.267187E+01 | -3.606720E-01 | -1.769922E+02 |

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|---|---|---|---|---|
| 8.702500E+08 | -2.364941E+01 | 8.521875E+01 | -3.666534E-01 | 1.718359E+02 |
| 9.196000E+08 | -2.448633E+01 | 8.806641E+01 | -3.780365E-01 | 1.605547E+02 |
| 9.689500E+08 | -2.505176E+01 | 9.084375E+01 | -3.873596E-01 | 1.492109E+02 |
| 1.018300E+09 | -2.538476E+01 | 9.375391E+01 | -4.087219E-01 | 1.377891E+02 |
| 1.067650E+09 | -2.551953E+01 | 9.648827E+01 | -4.220886E-01 | 1.262226E+02 |
| 1.117000E+09 | -2.543457E+01 | 9.913671E+01 | -4.419403E-01 | 1.146445E+02 |
| 1.166350E+09 | -2.512793E+01 | 1.018320E+02 | -4.645386E-01 | 1.029766E+02 |
| 1.215700E+09 | -2.456738E+01 | 1.042695E+02 | -4.959106E-01 | 9.126171E+01 |
| 1.265050E+09 | -2.355762E+01 | 1.062930E+02 | -5.152893E-01 | 7.944140E+01 |
| 1.314400E+09 | -2.167578E+01 | 1.063828E+02 | -5.361023E-01 | 6.758984E+01 |
| 1.363750E+09 | -2.010937E+01 | 9.508593E+01 | -5.620117E-01 | 5.563867E+01 |
| 1.413100E+09 | -1.930762E+01 | 8.237499E+01 | -5.903625E-01 | 4.359961E+01 |
| 1.462450E+09 | -1.890137E+01 | 6.932031E+01 | -6.113892E-01 | 3.150683E+01 |
| 1.511800E+09 | -1.879687E+01 | 5.607812E+01 | -6.365051E-01 | 1.927051E+01 |
| 1.561150E+09 | -1.894922E+01 | 4.244531E+01 | -6.506653E-01 | 6.952881E+00 |
| 1.610500E+09 | -1.928418E+01 | 2.881836E+01 | -6.719360E-01 | -5.427246E+00 |
| 1.659850E+09 | -1.983594E+01 | 1.491211E+01 | -6.900635E-01 | -1.799707E+01 |
| 1.709200E+09 | -2.052539E+01 | 9.379578E-01 | -7.081299E-01 | -3.065332E+01 |
| 1.758550E+09 | -2.135840E+01 | -1.270752E+01 | -7.241516E-01 | -4.348828E+01 |
| 1.807900E+09 | -2.231543E+01 | -2.658008E+01 | -7.448425E-01 | -5.638866E+01 |
| 1.857250E+09 | -2.330273E+01 | -3.980078E+01 | -7.733154E-01 | -6.950781E+01 |
| 1.906600E+09 | -2.444824E+01 | -5.169335E+01 | -8.014221E-01 | -8.273829E+01 |
| 1.955950E+09 | -2.558887E+01 | -6.287890E+01 | -8.319702E-01 | -9.614843E+01 |
| 2.005300E+09 | -2.659668E+01 | -7.102734E+01 | -8.667297E-01 | -1.097187E+02 |
| 2.054650E+09 | -2.733105E+01 | -7.650391E+01 | -8.996582E-01 | -1.234180E+02 |
| 2.104000E+09 | -2.761719E+01 | -8.049608E+01 | -9.391785E-01 | -1.372813E+02 |
| 2.153350E+09 | -2.754297E+01 | -8.382813E+01 | -9.923096E-01 | -1.512578E+02 |
| 2.202700E+09 | -2.705469E+01 | -8.674219E+01 | -1.058594E+00 | -1.653359E+02 |
| 2.252050E+09 | -2.626367E+01 | -8.914063E+01 | -1.121155E+00 | -1.795547E+02 |
| 2.301400E+09 | -2.512012E+01 | -9.176952E+01 | -1.192078E+00 | 1.662266E+02 |
| 2.350750E+09 | -2.367578E+01 | -9.402344E+01 | -1.286255E+00 | 1.518594E+02 |
| 2.400100E+09 | -2.202148E+01 | -9.702343E+01 | -1.386658E+00 | 1.374375E+02 |
| 2.449450E+09 | -2.003125E+01 | -1.013594E+02 | -1.503357E+00 | 1.230430E+02 |
| 2.498800E+09 | -1.788769E+01 | -1.063398E+02 | -1.655823E+00 | 1.086914E+02 |
| 2.548150E+09 | -1.571973E+01 | -1.143867E+02 | -1.812561E+00 | 9.443359E+01 |
| 2.597500E+09 | -1.366309E+01 | -1.249648E+02 | -2.022705E+00 | 8.019531E+01 |
| 2.646850E+09 | -1.189893E+01 | -1.367109E+02 | -2.194946E+00 | 6.611718E+01 |
| 2.696200E+09 | -1.034717E+01 | -1.490703E+02 | -2.448242E+00 | 5.239452E+01 |
| 2.745550E+09 | -9.029785E+00 | -1.614219E+02 | -2.696167E+00 | 3.852930E+01 |
| 2.794900E+09 | -7.886719E+00 | -1.742344E+02 | -2.960938E+00 | 2.545507E+01 |
| 2.844250E+09 | -6.924805E+00 | 1.731016E+02 | -3.269653E+00 | 1.234863E+01 |
| 2.893600E+09 | -6.126221E+00 | 1.605156E+02 | -3.568481E+00 | -1.950073E-01 |
| 2.942950E+09 | -5.459961E+00 | 1.481875E+02 | -3.885864E+00 | -1.249707E+01 |
| 2.992300E+09 | -4.911377E+00 | 1.361406E+02 | -4.174805E+00 | -2.429980E+01 |
| 3.041650E+09 | -4.460449E+00 | 1.243086E+02 | -4.461182E+00 | -3.556641E+01 |
| 3.091000E+09 | -4.100098E+00 | 1.127031E+02 | -4.765869E+00 | -4.653125E+01 |
| 3.140350E+09 | -3.814575E+00 | 1.014063E+02 | -4.968506E+00 | -5.730663E+01 |
| 3.189700E+09 | -3.588989E+00 | 9.017969E+01 | -5.203613E+00 | -6.724218E+01 |
| 3.239050E+09 | -3.423340E+00 | 7.922656E+01 | -5.394775E+00 | -7.738671E+01 |

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|---|---|---|---|---|
| 3.288400E+09 | -3.300171E+00 | 6.843359E+01 | -5.507324E+00 | -8.688280E+01 |
| 3.337750E+09 | -3.217041E+00 | 5.774414E+01 | -5.602295E+00 | -9.664843E+01 |
| 3.387100E+09 | -3.181885E+00 | 4.704492E+01 | -5.610352E+00 | -1.057383E+02 |
| 3.436450E+09 | -3.190063E+00 | 3.631250E+01 | -5.640869E+00 | -1.151563E+02 |
| 3.485800E+09 | -3.234375E+00 | 2.557422E+01 | -5.529297E+00 | -1.244609E+02 |
| 3.535150E+09 | -3.316528E+00 | 1.478467E+01 | -5.425293E+00 | -1.337188E+02 |
| 3.584500E+09 | -3.434814E+00 | 3.978394E+00 | -5.283691E+00 | -1.434219E+02 |
| 3.633850E+09 | -3.586548E+00 | -6.969482E+00 | -5.080811E+00 | -1.531953E+02 |
| 3.683200E+09 | -3.780273E+00 | -1.814551E+01 | -4.884521E+00 | -1.627578E+02 |
| 3.732550E+09 | -4.023193E+00 | -2.948633E+01 | -4.689941E+00 | -1.729141E+02 |
| 3.781900E+09 | -4.306885E+00 | -4.102344E+01 | -4.426025E+00 | 1.767344E+02 |
| 3.831250E+09 | -4.644775E+00 | -5.276953E+01 | -4.185059E+00 | 1.662969E+02 |
| 3.880600E+09 | -5.022949E+00 | -6.473046E+01 | -3.952637E+00 | 1.556484E+02 |
| 3.929950E+09 | -5.432129E+00 | -7.678905E+01 | -3.751587E+00 | 1.444922E+02 |
| 3.979300E+09 | -5.885254E+00 | -8.912889E+01 | -3.487793E+00 | 1.334297E+02 |
| 4.028650E+09 | -6.363770E+00 | -1.015820E+02 | -3.329468E+00 | 1.223711E+02 |
| 4.078000E+09 | -6.869385E+00 | -1.141562E+02 | -3.177979E+00 | 1.110234E+02 |
| 4.127350E+09 | -7.399170E+00 | -1.269844E+02 | -3.015869E+00 | 9.973436E+01 |
| 4.176700E+09 | -7.937500E+00 | -1.397266E+02 | -2.875854E+00 | 8.843750E+01 |
| 4.226050E+09 | -8.470215E+00 | -1.525781E+02 | -2.767334E+00 | 7.704296E+01 |
| 4.275400E+09 | -8.987793E+00 | -1.654766E+02 | -2.658936E+00 | 6.560547E+01 |
| 4.324750E+09 | -9.507324E+00 | -1.782891E+02 | -2.561768E+00 | 5.434765E+01 |
| 4.374100E+09 | -1.003564E+01 | 1.689453E+02 | -2.493286E+00 | 4.299218E+01 |
| 4.423450E+09 | -1.056250E+01 | 1.563125E+02 | -2.420288E+00 | 3.165234E+01 |
| 4.472800E+09 | -1.112793E+01 | 1.438203E+02 | -2.342651E+00 | 2.034375E+01 |
| 4.522150E+09 | -1.173047E+01 | 1.318438E+02 | -2.286865E+00 | 9.030762E+00 |
| 4.571500E+09 | -1.244580E+01 | 1.201953E+02 | -2.228760E+00 | -2.390991E+00 |
| 4.620850E+09 | -1.326953E+01 | 1.093945E+02 | -2.165039E+00 | -1.394189E+01 |
| 4.670200E+09 | -1.431738E+01 | 1.005781E+02 | -2.110474E+00 | -2.546679E+01 |
| 4.719550E+09 | -1.545654E+01 | 9.452734E+01 | -2.071289E+00 | -3.713867E+01 |
| 4.768900E+09 | -1.631055E+01 | 9.191015E+01 | -2.047974E+00 | -4.897655E+01 |
| 4.818250E+09 | -1.683789E+01 | 9.113281E+01 | -2.025269E+00 | -6.098046E+01 |
| 4.867600E+09 | -1.705664E+01 | 9.086329E+01 | -2.027344E+00 | -7.301562E+01 |
| 4.916950E+09 | -1.698242E+01 | 9.104296E+01 | -2.068359E+00 | -8.525391E+01 |
| 4.966300E+09 | -1.670801E+01 | 9.137110E+01 | -2.126831E+00 | -9.766405E+01 |
| 5.015650E+09 | -1.622070E+01 | 9.160936E+01 | -2.212036E+00 | -1.101484E+02 |
| 5.065000E+09 | -1.553271E+01 | 9.156250E+01 | -2.343262E+00 | -1.227305E+02 |
| 5.114350E+09 | -1.462354E+01 | 9.120703E+01 | -2.510376E+00 | -1.354453E+02 |
| 5.163700E+09 | -1.350293E+01 | 9.014452E+01 | -2.706543E+00 | -1.481719E+02 |
| 5.213050E+09 | -1.208398E+01 | 8.728907E+01 | -2.926636E+00 | -1.609219E+02 |
| 5.262400E+09 | -1.052783E+01 | 8.167578E+01 | -3.165894E+00 | -1.737734E+02 |
| 5.311750E+09 | -9.230469E+00 | 7.294922E+01 | -3.414307E+00 | 1.733672E+02 |
| 5.361100E+09 | -8.269043E+00 | 6.266015E+01 | -3.684570E+00 | 1.602890E+02 |
| 5.410450E+09 | -7.648926E+00 | 5.219727E+01 | -3.934204E+00 | 1.469141E+02 |
| 5.459800E+09 | -7.362549E+00 | 4.214063E+01 | -4.199951E+00 | 1.331953E+02 |
| 5.509150E+09 | -7.269287E+00 | 3.338281E+01 | -4.501709E+00 | 1.187930E+02 |
| 5.558500E+09 | -7.224609E+00 | 2.624218E+01 | -4.851074E+00 | 1.037305E+02 |
| 5.607850E+09 | -7.127441E+00 | 2.005762E+01 | -5.291260E+00 | 8.791796E+01 |
| 5.657200E+09 | -6.958740E+00 | 1.428467E+01 | -5.868652E+00 | 7.160546E+01 |

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|---|---|---|---|---|
| 5.706550E+09 | -6.740967E+00 | 8.618652E+00 | -6.576416E+00 | 5.491601E+01 |
| 5.755900E+09 | -6.481934E+00 | 3.066528E+00 | -7.431152E+00 | 3.800390E+01 |
| 5.805250E+09 | -6.181396E+00 | -2.427979E+00 | -8.457031E+00 | 2.117285E+01 |
| 5.854600E+09 | -5.851318E+00 | -7.968018E+00 | -9.594238E+00 | 4.096436E+00 |
| 5.903950E+09 | -5.452148E+00 | -1.350781E+01 | -1.082910E+01 | -1.272510E+01 |
| 5.953300E+09 | -4.970947E+00 | -1.928711E+01 | -1.220361E+01 | -2.918164E+01 |
| 6.002650E+09 | -4.376465E+00 | -2.570605E+01 | -1.362451E+01 | -4.556445E+01 |
| 6.052000E+09 | -3.742554E+00 | -3.343750E+01 | -1.506104E+01 | -6.125977E+01 |
| 6.101350E+09 | -3.188843E+00 | -4.263672E+01 | -1.651855E+01 | -7.648046E+01 |
| 6.150700E+09 | -2.784302E+00 | -5.265429E+01 | -1.786035E+01 | -9.114843E+01 |
| 6.200050E+09 | -2.526489E+00 | -6.289844E+01 | -1.908008E+01 | -1.053164E+02 |
| 6.249400E+09 | -2.371094E+00 | -7.318359E+01 | -2.008594E+01 | -1.193516E+02 |
| 6.298750E+09 | -2.295532E+00 | -8.353907E+01 | -2.090039E+01 | -1.329062E+02 |
| 6.348100E+09 | -2.273560E+00 | -9.400391E+01 | -2.146191E+01 | -1.468594E+02 |
| 6.397450E+09 | -2.281616E+00 | -1.045430E+02 | -2.181250E+01 | -1.602734E+02 |
| 6.446800E+09 | -2.333984E+00 | -1.153086E+02 | -2.197656E+01 | -1.736875E+02 |
| 6.496150E+09 | -2.400269E+00 | -1.263086E+02 | -2.195019E+01 | 1.728359E+02 |
| 6.545500E+09 | -2.496948E+00 | -1.376328E+02 | -2.177344E+01 | 1.597422E+02 |
| 6.594850E+09 | -2.600098E+00 | -1.493203E+02 | -2.144433E+01 | 1.469844E+02 |
| 6.644200E+09 | -2.715698E+00 | -1.613125E+02 | -2.095313E+01 | 1.343516E+02 |
| 6.693550E+09 | -2.850342E+00 | -1.737656E+02 | -2.037890E+01 | 1.221484E+02 |
| 6.742900E+09 | -2.983276E+00 | 1.733828E+02 | -1.967383E+01 | 1.100195E+02 |
| 6.792250E+09 | -3.126953E+00 | 1.601484E+02 | -1.896582E+01 | 9.846874E+01 |
| 6.841600E+09 | -3.259033E+00 | 1.465781E+02 | -1.821289E+01 | 8.645311E+01 |
| 6.890950E+09 | -3.388550E+00 | 1.327812E+02 | -1.743750E+01 | 7.517187E+01 |
| 6.940300E+09 | -3.511719E+00 | 1.187344E+02 | -1.673340E+01 | 6.363671E+01 |
| 6.989650E+09 | -3.627197E+00 | 1.045859E+02 | -1.600488E+01 | 5.211132E+01 |
| 7.039000E+09 | -3.732056E+00 | 9.044922E+01 | -1.527344E+01 | 4.072656E+01 |
| 7.088350E+09 | -3.815430E+00 | 7.640625E+01 | -1.456494E+01 | 2.934765E+01 |
| 7.137700E+09 | -3.891235E+00 | 6.257421E+01 | -1.392334E+01 | 1.789355E+01 |
| 7.187050E+09 | -3.953735E+00 | 4.895898E+01 | -1.331836E+01 | 6.386963E+00 |
| 7.236400E+09 | -4.001709E+00 | 3.567968E+01 | -1.267725E+01 | -5.155518E+00 |
| 7.285750E+09 | -4.055664E+00 | 2.273438E+01 | -1.216406E+01 | -1.609961E+01 |
| 7.335100E+09 | -4.103027E+00 | 1.027051E+01 | -1.169482E+01 | -2.799609E+01 |
| 7.384450E+09 | -4.179443E+00 | -1.786682E+00 | -1.115381E+01 | -3.924219E+01 |
| 7.433800E+09 | -4.278320E+00 | -1.340771E+01 | -1.074316E+01 | -5.039844E+01 |
| 7.483150E+09 | -4.414307E+00 | -2.448339E+01 | -1.031299E+01 | -6.182226E+01 |
| 7.532500E+09 | -4.604980E+00 | -3.518750E+01 | -9.901367E+00 | -7.329687E+01 |
| 7.581850E+09 | -4.864502E+00 | -4.530273E+01 | -9.504395E+00 | -8.449610E+01 |
| 7.631200E+09 | -5.236084E+00 | -5.472070E+01 | -9.138184E+00 | -9.581249E+01 |
| 7.680550E+09 | -5.714355E+00 | -6.327734E+01 | -8.746582E+00 | -1.075781E+02 |
| 7.729900E+09 | -6.246826E+00 | -7.027734E+01 | -8.337891E+00 | -1.192851E+02 |
| 7.779250E+09 | -6.780273E+00 | -7.572656E+01 | -8.072754E+00 | -1.311719E+02 |
| 7.828600E+09 | -7.209717E+00 | -7.985546E+01 | -7.757080E+00 | -1.443750E+02 |
| 7.877950E+09 | -7.508301E+00 | -8.314062E+01 | -7.460449E+00 | -1.565312E+02 |
| 7.927300E+09 | -7.681152E+00 | -8.593359E+01 | -7.349854E+00 | -1.697109E+02 |
| 7.976650E+09 | -7.733398E+00 | -8.842188E+01 | -7.238770E+00 | 1.769375E+02 |
| 8.026000E+09 | -7.696289E+00 | -9.087109E+01 | -7.193115E+00 | 1.638281E+02 |
| 8.075350E+09 | -7.548340E+00 | -9.320704E+01 | -7.254883E+00 | 1.508594E+02 |

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|---|---|---|---|---|
| 8.124700E+09 | -7.302246E+00 | -9.566797E+01 | -7.385254E+00 | 1.375703E+02 |
| 8.174050E+09 | -6.942871E+00 | -9.849218E+01 | -7.602051E+00 | 1.247852E+02 |
| 8.223400E+09 | -6.468018E+00 | -1.017969E+02 | -7.818115E+00 | 1.119922E+02 |
| 8.272750E+09 | -5.952881E+00 | -1.063203E+02 | -8.131348E+00 | 9.990623E+01 |
| 8.322100E+09 | -5.447266E+00 | -1.120078E+02 | -8.395508E+00 | 8.746874E+01 |
| 8.371450E+09 | -5.078369E+00 | -1.185547E+02 | -8.704590E+00 | 7.619922E+01 |
| 8.420800E+09 | -4.882813E+00 | -1.256250E+02 | -8.961426E+00 | 6.379101E+01 |
| 8.470150E+09 | -4.811279E+00 | -1.325625E+02 | -9.209961E+00 | 5.229492E+01 |
| 8.519500E+09 | -4.860352E+00 | -1.390547E+02 | -9.470215E+00 | 3.979883E+01 |
| 8.568850E+09 | -4.949707E+00 | -1.449922E+02 | -9.775391E+00 | 2.692578E+01 |
| 8.618200E+09 | -5.028809E+00 | -1.504062E+02 | -1.013672E+01 | 1.377930E+01 |
| 8.667550E+09 | -5.078613E+00 | -1.557969E+02 | -1.072949E+01 | 2.362061E-01 |
| 8.716900E+09 | -5.085205E+00 | -1.612109E+02 | -1.136426E+01 | -1.394873E+01 |
| 8.766250E+09 | -5.080811E+00 | -1.668984E+02 | -1.233301E+01 | -2.677734E+01 |
| 8.815600E+09 | -5.055664E+00 | -1.729609E+02 | -1.344873E+01 | -3.919922E+01 |
| 8.864950E+09 | -5.028320E+00 | -1.794062E+02 | -1.474707E+01 | -4.951757E+01 |
| 8.914300E+09 | -4.985596E+00 | 1.734375E+02 | -1.596436E+01 | -5.823242E+01 |
| 8.963650E+09 | -4.918701E+00 | 1.656094E+02 | -1.718554E+01 | -6.440624E+01 |
| 9.013000E+09 | -4.884033E+00 | 1.566484E+02 | -1.818750E+01 | -7.036327E+01 |
| 9.062350E+09 | -4.853516E+00 | 1.462578E+02 | -1.905664E+01 | -7.479297E+01 |
| 9.111700E+09 | -4.894775E+00 | 1.344609E+02 | -1.973926E+01 | -7.863281E+01 |
| 9.161050E+09 | -5.025391E+00 | 1.209375E+02 | -2.028515E+01 | -8.221094E+01 |
| 9.210400E+09 | -5.235596E+00 | 1.062656E+02 | -2.052246E+01 | -8.571093E+01 |
| 9.259750E+09 | -5.498779E+00 | 9.037889E+01 | -2.063574E+01 | -8.878906E+01 |
| 9.309100E+09 | -5.746338E+00 | 7.358593E+01 | -2.047070E+01 | -9.325390E+01 |
| 9.358450E+09 | -5.973633E+00 | 5.602148E+01 | -2.014746E+01 | -9.856640E+01 |
| 9.407800E+09 | -6.129639E+00 | 3.795117E+01 | -1.973437E+01 | -1.059375E+02 |
| 9.457150E+09 | -6.227295E+00 | 1.977344E+01 | -1.941504E+01 | -1.150625E+02 |
| 9.506500E+09 | -6.238770E+00 | 1.466675E+00 | -1.927148E+01 | -1.259219E+02 |
| 9.555850E+09 | -6.148438E+00 | -1.639941E+01 | -1.938281E+01 | -1.367188E+02 |
| 9.605200E+09 | -6.000000E+00 | -3.374609E+01 | -1.972656E+01 | -1.480547E+02 |
| 9.654550E+09 | -5.748047E+00 | -5.042382E+01 | -2.027344E+01 | -1.586484E+02 |
| 9.703900E+09 | -5.459717E+00 | -6.605859E+01 | -2.101758E+01 | -1.685859E+02 |
| 9.753250E+09 | -5.116455E+00 | -8.067968E+01 | -2.188769E+01 | -1.767812E+02 |
| 9.802600E+09 | -4.770020E+00 | -9.326172E+01 | -2.276367E+01 | 1.759297E+02 |
| 9.851950E+09 | -4.452881E+00 | -1.040000E+02 | -2.362793E+01 | 1.700703E+02 |
| 9.901300E+09 | -4.161621E+00 | -1.128828E+02 | -2.445508E+01 | 1.651641E+02 |
| 9.950650E+09 | -3.931763E+00 | -1.202266E+02 | -2.519922E+01 | 1.616953E+02 |
| 1.000000E+10 | -3.732056E+00 | -1.262226E+02 | -2.589453E+01 | 1.590469E+02 |

## A.13. 130-mil wide N-shaped structure with 2S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -2.300781E+01 | -1.404297E+02 | -9.586334E-02 | -4.084180E+01 |
| 1.793500E+08 | -2.238476E+01 | -1.465859E+02 | -1.087723E-01 | -4.640234E+01 |
| 2.287000E+08 | -2.173828E+01 | -1.537656E+02 | -1.215897E-01 | -5.288086E+01 |
| 2.780500E+08 | -2.111230E+01 | -1.618828E+02 | -1.351852E-01 | -6.027148E+01 |

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|---|---|---|---|---|
| 3.274000E+08 | -2.049707E+01 | -1.711016E+02 | -1.516800E-01 | -6.858593E+01 |
| 3.767500E+08 | -1.991699E+01 | 1.786719E+02 | -1.680756E-01 | -7.780859E+01 |
| 4.261000E+08 | -1.940918E+01 | 1.673672E+02 | -1.846542E-01 | -8.795313E+01 |
| 4.754500E+08 | -1.918262E+01 | 1.560469E+02 | -2.043152E-01 | -9.807421E+01 |
| 5.248000E+08 | -1.924902E+01 | 1.447813E+02 | -2.131805E-01 | -1.082109E+02 |
| 5.741500E+08 | -1.957715E+01 | 1.333516E+02 | -2.297668E-01 | -1.183750E+02 |
| 6.235000E+08 | -2.019922E+01 | 1.221172E+02 | -2.372513E-01 | -1.285312E+02 |
| 6.728500E+08 | -2.121973E+01 | 1.108320E+02 | -2.486877E-01 | -1.387031E+02 |
| 7.222000E+08 | -2.287109E+01 | 1.006875E+02 | -2.550812E-01 | -1.488906E+02 |
| 7.715500E+08 | -2.520215E+01 | 1.020469E+02 | -2.610016E-01 | -1.591250E+02 |
| 8.209000E+08 | -2.656738E+01 | 1.051445E+02 | -2.708740E-01 | -1.693750E+02 |
| 8.702500E+08 | -2.740332E+01 | 1.087656E+02 | -2.782745E-01 | -1.796328E+02 |
| 9.196000E+08 | -2.799414E+01 | 1.127109E+02 | -2.868652E-01 | 1.700391E+02 |
| 9.689500E+08 | -2.832715E+01 | 1.164180E+02 | -2.986603E-01 | 1.597422E+02 |
| 1.018300E+09 | -2.843945E+01 | 1.204453E+02 | -3.183746E-01 | 1.493906E+02 |
| 1.067650E+09 | -2.835938E+01 | 1.243008E+02 | -3.334351E-01 | 1.390000E+02 |
| 1.117000E+09 | -2.804785E+01 | 1.281484E+02 | -3.487396E-01 | 1.286250E+02 |
| 1.166350E+09 | -2.748730E+01 | 1.320781E+02 | -3.705597E-01 | 1.181836E+02 |
| 1.215700E+09 | -2.657812E+01 | 1.357422E+02 | -3.932037E-01 | 1.077422E+02 |
| 1.265050E+09 | -2.505762E+01 | 1.384922E+02 | -4.140472E-01 | 9.725389E+01 |
| 1.314400E+09 | -2.293555E+01 | 1.297109E+02 | -4.352722E-01 | 8.681250E+01 |
| 1.363750E+09 | -2.178418E+01 | 1.189687E+02 | -4.551697E-01 | 7.632030E+01 |
| 1.413100E+09 | -2.122656E+01 | 1.078906E+02 | -4.763336E-01 | 6.576953E+01 |
| 1.462450E+09 | -2.096094E+01 | 9.633202E+01 | -4.978333E-01 | 5.524023E+01 |
| 1.511800E+09 | -2.098437E+01 | 8.509375E+01 | -5.193481E-01 | 4.464648E+01 |
| 1.561150E+09 | -2.123926E+01 | 7.308594E+01 | -5.328979E-01 | 3.404492E+01 |
| 1.610500E+09 | -2.165722E+01 | 6.099999E+01 | -5.601807E-01 | 2.343652E+01 |
| 1.659850E+09 | -2.238965E+01 | 4.766406E+01 | -5.855713E-01 | 1.281543E+01 |
| 1.709200E+09 | -2.333496E+01 | 3.416601E+01 | -6.110840E-01 | 2.224731E+00 |
| 1.758550E+09 | -2.438965E+01 | 2.095019E+01 | -6.328735E-01 | -8.397949E+00 |
| 1.807900E+09 | -2.525097E+01 | 6.201660E+00 | -6.564026E-01 | -1.906445E+01 |
| 1.857250E+09 | -2.600293E+01 | -8.198730E+00 | -6.858826E-01 | -2.976660E+01 |
| 1.906600E+09 | -2.658203E+01 | -2.371875E+01 | -7.178040E-01 | -4.047656E+01 |
| 1.955950E+09 | -2.685351E+01 | -3.918554E+01 | -7.509766E-01 | -5.121288E+01 |
| 2.005300E+09 | -2.697949E+01 | -5.490039E+01 | -7.913513E-01 | -6.193359E+01 |
| 2.054650E+09 | -2.680566E+01 | -7.064453E+01 | -8.330994E-01 | -7.266406E+01 |
| 2.104000E+09 | -2.644238E+01 | -8.536718E+01 | -8.761902E-01 | -8.344530E+01 |
| 2.153350E+09 | -2.586328E+01 | -9.991014E+01 | -9.084778E-01 | -9.412500E+01 |
| 2.202700E+09 | -2.495019E+01 | -1.127969E+02 | -9.398193E-01 | -1.047539E+02 |
| 2.252050E+09 | -2.372559E+01 | -1.252461E+02 | -9.694824E-01 | -1.155391E+02 |
| 2.301400E+09 | -2.224316E+01 | -1.376641E+02 | -9.981079E-01 | -1.263164E+02 |
| 2.350750E+09 | -2.087109E+01 | -1.486875E+02 | -1.035400E+00 | -1.370547E+02 |
| 2.400100E+09 | -1.948340E+01 | -1.601250E+02 | -1.082886E+00 | -1.478281E+02 |
| 2.449450E+09 | -1.817383E+01 | -1.701406E+02 | -1.124146E+00 | -1.585391E+02 |
| 2.498800E+09 | -1.705566E+01 | 1.797109E+02 | -1.173706E+00 | -1.691406E+02 |
| 2.548150E+09 | -1.593604E+01 | 1.700234E+02 | -1.213440E+00 | -1.798203E+02 |
| 2.597500E+09 | -1.498486E+01 | 1.603984E+02 | -1.271484E+00 | 1.695859E+02 |
| 2.646850E+09 | -1.408301E+01 | 1.502422E+02 | -1.318237E+00 | 1.589453E+02 |
| 2.696200E+09 | -1.327930E+01 | 1.400938E+02 | -1.369385E+00 | 1.485156E+02 |

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|---|---|---|---|---|
| 2.745550E+09 | -1.259766E+01 | 1.295938E+02 | -1.448730E+00 | 1.379297E+02 |
| 2.794900E+09 | -1.202393E+01 | 1.186719E+02 | -1.499084E+00 | 1.275664E+02 |
| 2.844250E+09 | -1.163623E+01 | 1.077812E+02 | -1.571960E+00 | 1.172969E+02 |
| 2.893600E+09 | -1.134326E+01 | 9.689842E+01 | -1.623108E+00 | 1.071328E+02 |
| 2.942950E+09 | -1.114014E+01 | 8.622265E+01 | -1.668457E+00 | 9.702734E+01 |
| 2.992300E+09 | -1.106689E+01 | 7.524219E+01 | -1.694641E+00 | 8.689453E+01 |
| 3.041650E+09 | -1.109521E+01 | 6.420703E+01 | -1.706604E+00 | 7.683203E+01 |
| 3.091000E+09 | -1.128711E+01 | 5.331640E+01 | -1.725525E+00 | 6.689062E+01 |
| 3.140350E+09 | -1.158789E+01 | 4.232617E+01 | -1.713440E+00 | 5.674999E+01 |
| 3.189700E+09 | -1.207422E+01 | 3.158789E+01 | -1.681213E+00 | 4.685937E+01 |
| 3.239050E+09 | -1.271240E+01 | 2.071582E+01 | -1.661316E+00 | 3.669140E+01 |
| 3.288400E+09 | -1.350049E+01 | 1.007715E+01 | -1.597107E+00 | 2.653125E+01 |
| 3.337750E+09 | -1.459814E+01 | -9.008789E-01 | -1.566101E+00 | 1.627539E+01 |
| 3.387100E+09 | -1.595459E+01 | -1.183105E+01 | -1.501465E+00 | 5.955811E+00 |
| 3.436450E+09 | -1.817187E+01 | -2.259570E+01 | -1.463135E+00 | -4.490723E+00 |
| 3.485800E+09 | -2.104297E+01 | -1.646484E+01 | -1.410583E+00 | -1.496631E+01 |
| 3.535150E+09 | -2.270801E+01 | -1.305176E+01 | -1.374268E+00 | -2.544238E+01 |
| 3.584500E+09 | -2.394726E+01 | -7.940430E+00 | -1.345154E+00 | -3.610547E+01 |
| 3.633850E+09 | -2.510156E+01 | -3.198486E+00 | -1.310852E+00 | -4.681836E+01 |
| 3.683200E+09 | -2.594043E+01 | 1.365051E+00 | -1.286560E+00 | -5.743945E+01 |
| 3.732550E+09 | -2.660254E+01 | 6.472168E+00 | -1.295593E+00 | -6.822266E+01 |
| 3.781900E+09 | -2.715039E+01 | 1.125391E+01 | -1.286804E+00 | -7.904297E+01 |
| 3.831250E+09 | -2.751758E+01 | 1.649023E+01 | -1.295959E+00 | -8.979296E+01 |
| 3.880600E+09 | -2.779199E+01 | 2.180176E+01 | -1.309509E+00 | -1.005781E+02 |
| 3.929950E+09 | -2.786426E+01 | 2.735644E+01 | -1.327332E+00 | -1.114023E+02 |
| 3.979300E+09 | -2.729785E+01 | 3.419531E+01 | -1.340576E+00 | -1.222461E+02 |
| 4.028650E+09 | -2.638379E+01 | 2.476855E+01 | -1.362671E+00 | -1.331797E+02 |
| 4.078000E+09 | -2.678711E+01 | 2.197461E+01 | -1.398071E+00 | -1.441562E+02 |
| 4.127350E+09 | -2.764355E+01 | 2.089844E+01 | -1.429871E+00 | -1.551016E+02 |
| 4.176700E+09 | -2.820703E+01 | 2.189160E+01 | -1.467957E+00 | -1.661328E+02 |
| 4.226050E+09 | -2.867969E+01 | 2.548633E+01 | -1.510681E+00 | -1.772109E+02 |
| 4.275400E+09 | -2.919922E+01 | 2.862695E+01 | -1.556335E+00 | 1.717734E+02 |
| 4.324750E+09 | -2.945019E+01 | 3.186816E+01 | -1.612549E+00 | 1.606641E+02 |
| 4.374100E+09 | -2.977930E+01 | 3.661328E+01 | -1.669373E+00 | 1.495312E+02 |
| 4.423450E+09 | -3.010547E+01 | 4.275586E+01 | -1.720520E+00 | 1.383437E+02 |
| 4.472800E+09 | -3.029687E+01 | 4.975195E+01 | -1.781555E+00 | 1.271211E+02 |
| 4.522150E+09 | -3.015820E+01 | 5.889062E+01 | -1.844788E+00 | 1.158320E+02 |
| 4.571500E+09 | -2.946386E+01 | 6.805078E+01 | -1.912781E+00 | 1.046094E+02 |
| 4.620850E+09 | -2.826367E+01 | 7.478906E+01 | -1.975769E+00 | 9.331640E+01 |
| 4.670200E+09 | -2.679785E+01 | 7.927343E+01 | -2.045410E+00 | 8.196093E+01 |
| 4.719550E+09 | -2.542480E+01 | 8.176561E+01 | -2.119995E+00 | 7.058203E+01 |
| 4.768900E+09 | -2.420215E+01 | 8.230860E+01 | -2.202148E+00 | 5.924218E+01 |
| 4.818250E+09 | -2.284375E+01 | 8.268749E+01 | -2.287842E+00 | 4.777929E+01 |
| 4.867600E+09 | -2.163379E+01 | 8.362890E+01 | -2.380737E+00 | 3.641797E+01 |
| 4.916950E+09 | -2.027246E+01 | 8.250780E+01 | -2.471313E+00 | 2.502930E+01 |
| 4.966300E+09 | -1.862305E+01 | 8.013281E+01 | -2.578125E+00 | 1.364893E+01 |
| 5.015650E+09 | -1.698047E+01 | 7.687109E+01 | -2.688477E+00 | 2.389526E+00 |
| 5.065000E+09 | -1.541357E+01 | 6.984375E+01 | -2.802246E+00 | -8.829102E+00 |
| 5.114350E+09 | -1.402734E+01 | 6.214257E+01 | -2.912109E+00 | -2.000683E+01 |

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|---|---|---|---|---|
| 5.163700E+09 | -1.297900E+01 | 5.324219E+01 | -3.020142E+00 | -3.106250E+01 |
| 5.213050E+09 | -1.207813E+01 | 4.331445E+01 | -3.125122E+00 | -4.201172E+01 |
| 5.262400E+09 | -1.138330E+01 | 3.364062E+01 | -3.219116E+00 | -5.285546E+01 |
| 5.311750E+09 | -1.089209E+01 | 2.342383E+01 | -3.287598E+00 | -6.365234E+01 |
| 5.361100E+09 | -1.054346E+01 | 1.334521E+01 | -3.353027E+00 | -7.429688E+01 |
| 5.410450E+09 | -1.038867E+01 | 3.268433E+00 | -3.387085E+00 | -8.496874E+01 |
| 5.459800E+09 | -1.036523E+01 | -6.856934E+00 | -3.407715E+00 | -9.552734E+01 |
| 5.509150E+09 | -1.052734E+01 | -1.658691E+01 | -3.412476E+00 | -1.060547E+02 |
| 5.558500E+09 | -1.084717E+01 | -2.651758E+01 | -3.386719E+00 | -1.166953E+02 |
| 5.607850E+09 | -1.133887E+01 | -3.575390E+01 | -3.341919E+00 | -1.272969E+02 |
| 5.657200E+09 | -1.211523E+01 | -4.439453E+01 | -3.283447E+00 | -1.380000E+02 |
| 5.706550E+09 | -1.307666E+01 | -5.215234E+01 | -3.213379E+00 | -1.488359E+02 |
| 5.755900E+09 | -1.428418E+01 | -5.699023E+01 | -3.137207E+00 | -1.597500E+02 |
| 5.805250E+09 | -1.551855E+01 | -5.975780E+01 | -3.061890E+00 | -1.707031E+02 |
| 5.854600E+09 | -1.648535E+01 | -6.047656E+01 | -2.991211E+00 | 1.781953E+02 |
| 5.903950E+09 | -1.730469E+01 | -5.978710E+01 | -2.904541E+00 | 1.670078E+02 |
| 5.953300E+09 | -1.792578E+01 | -5.908789E+01 | -2.844482E+00 | 1.558125E+02 |
| 6.002650E+09 | -1.833203E+01 | -5.775000E+01 | -2.793213E+00 | 1.444375E+02 |
| 6.052000E+09 | -1.867285E+01 | -5.642187E+01 | -2.736816E+00 | 1.330859E+02 |
| 6.101350E+09 | -1.882422E+01 | -5.545507E+01 | -2.704712E+00 | 1.217383E+02 |
| 6.150700E+09 | -1.884180E+01 | -5.439648E+01 | -2.673706E+00 | 1.103789E+02 |
| 6.200050E+09 | -1.872461E+01 | -5.418359E+01 | -2.654907E+00 | 9.899609E+01 |
| 6.249400E+09 | -1.847168E+01 | -5.488476E+01 | -2.638184E+00 | 8.766796E+01 |
| 6.298750E+09 | -1.820313E+01 | -5.818359E+01 | -2.630981E+00 | 7.633594E+01 |
| 6.348100E+09 | -1.809473E+01 | -6.375977E+01 | -2.618286E+00 | 6.489062E+01 |
| 6.397450E+09 | -1.861914E+01 | -6.936718E+01 | -2.618042E+00 | 5.354297E+01 |
| 6.446800E+09 | -1.992480E+01 | -7.267187E+01 | -2.620361E+00 | 4.214063E+01 |
| 6.496150E+09 | -2.083301E+01 | -7.098827E+01 | -2.625244E+00 | 3.065136E+01 |
| 6.545500E+09 | -2.140137E+01 | -6.777344E+01 | -2.633179E+00 | 1.924219E+01 |
| 6.594850E+09 | -2.173730E+01 | -6.480469E+01 | -2.656616E+00 | 7.728760E+00 |
| 6.644200E+09 | -2.187891E+01 | -6.136719E+01 | -2.678589E+00 | -3.799927E+00 |
| 6.693550E+09 | -2.193066E+01 | -5.806445E+01 | -2.709229E+00 | -1.537402E+01 |
| 6.742900E+09 | -2.180957E+01 | -5.502539E+01 | -2.750366E+00 | -2.690918E+01 |
| 6.792250E+09 | -2.156543E+01 | -5.165234E+01 | -2.800781E+00 | -3.853320E+01 |
| 6.841600E+09 | -2.115332E+01 | -4.881054E+01 | -2.849731E+00 | -5.008789E+01 |
| 6.890950E+09 | -2.052734E+01 | -4.578321E+01 | -2.912720E+00 | -6.166797E+01 |
| 6.940300E+09 | -1.959570E+01 | -4.405469E+01 | -2.969727E+00 | -7.322656E+01 |
| 6.989650E+09 | -1.815527E+01 | -4.642578E+01 | -3.042847E+00 | -8.480860E+01 |
| 7.039000E+09 | -1.733398E+01 | -5.275781E+01 | -3.110229E+00 | -9.636719E+01 |
| 7.088350E+09 | -1.727148E+01 | -5.999413E+01 | -3.182617E+00 | -1.079414E+02 |
| 7.137700E+09 | -1.751269E+01 | -6.505468E+01 | -3.239258E+00 | -1.194180E+02 |
| 7.187050E+09 | -1.784961E+01 | -6.658593E+01 | -3.308228E+00 | -1.309922E+02 |
| 7.236400E+09 | -1.807617E+01 | -6.702734E+01 | -3.363281E+00 | -1.426641E+02 |
| 7.285750E+09 | -1.807031E+01 | -6.616796E+01 | -3.422363E+00 | -1.541719E+02 |
| 7.335100E+09 | -1.799414E+01 | -6.497265E+01 | -3.513184E+00 | -1.659531E+02 |
| 7.384450E+09 | -1.774902E+01 | -6.376367E+01 | -3.562866E+00 | -1.777734E+02 |
| 7.433800E+09 | -1.737890E+01 | -6.222070E+01 | -3.656006E+00 | 1.706953E+02 |
| 7.483150E+09 | -1.689258E+01 | -6.111914E+01 | -3.769409E+00 | 1.588906E+02 |
| 7.532500E+09 | -1.618848E+01 | -5.979687E+01 | -3.862549E+00 | 1.470312E+02 |

| | | | | |
|---|---|---|---|---|
| 7.581850E+09 | -1.535693E+01 | -5.939648E+01 | -3.950317E+00 | 1.355156E+02 |
| 7.631200E+09 | -1.425439E+01 | -6.039063E+01 | -4.073975E+00 | 1.239805E+02 |
| 7.680550E+09 | -1.303906E+01 | -6.311523E+01 | -4.211914E+00 | 1.123906E+02 |
| 7.729900E+09 | -1.206934E+01 | -6.942577E+01 | -4.295166E+00 | 1.008906E+02 |
| 7.779250E+09 | -1.130664E+01 | -7.711328E+01 | -4.423828E+00 | 8.987499E+01 |
| 7.828600E+09 | -1.094873E+01 | -8.501562E+01 | -4.549561E+00 | 7.826172E+01 |
| 7.877950E+09 | -1.082813E+01 | -9.320704E+01 | -4.592041E+00 | 6.730078E+01 |
| 7.927300E+09 | -1.093018E+01 | -1.002891E+02 | -4.696777E+00 | 5.613867E+01 |
| 7.976650E+09 | -1.131592E+01 | -1.065234E+02 | -4.736572E+00 | 4.486718E+01 |
| 8.026000E+09 | -1.171387E+01 | -1.113672E+02 | -4.756836E+00 | 3.374804E+01 |
| 8.075350E+09 | -1.215625E+01 | -1.138750E+02 | -4.790527E+00 | 2.270801E+01 |
| 8.124700E+09 | -1.257324E+01 | -1.156602E+02 | -4.816650E+00 | 1.127979E+01 |
| 8.174050E+09 | -1.280469E+01 | -1.165586E+02 | -4.832031E+00 | -1.208496E-01 |
| 8.223400E+09 | -1.296191E+01 | -1.170781E+02 | -4.812988E+00 | -1.169385E+01 |
| 8.272750E+09 | -1.295508E+01 | -1.174375E+02 | -4.864990E+00 | -2.300683E+01 |
| 8.322100E+09 | -1.286182E+01 | -1.172930E+02 | -4.872070E+00 | -3.490234E+01 |
| 8.371450E+09 | -1.269287E+01 | -1.179492E+02 | -4.898438E+00 | -4.610742E+01 |
| 8.420800E+09 | -1.235059E+01 | -1.189336E+02 | -4.926758E+00 | -5.791406E+01 |
| 8.470150E+09 | -1.194287E+01 | -1.202461E+02 | -4.951660E+00 | -6.909374E+01 |
| 8.519500E+09 | -1.144873E+01 | -1.229375E+02 | -4.976563E+00 | -8.064844E+01 |
| 8.568850E+09 | -1.102539E+01 | -1.268633E+02 | -4.994873E+00 | -9.212109E+01 |
| 8.618200E+09 | -1.074951E+01 | -1.330000E+02 | -4.973145E+00 | -1.035000E+02 |
| 8.667550E+09 | -1.061035E+01 | -1.395625E+02 | -4.999268E+00 | -1.149141E+02 |
| 8.716900E+09 | -1.091895E+01 | -1.455000E+02 | -4.937744E+00 | -1.265430E+02 |
| 8.766250E+09 | -1.154736E+01 | -1.513906E+02 | -4.926758E+00 | -1.380391E+02 |
| 8.815600E+09 | -1.221631E+01 | -1.543359E+02 | -4.876221E+00 | -1.498750E+02 |
| 8.864950E+09 | -1.287598E+01 | -1.550703E+02 | -4.846924E+00 | -1.617109E+02 |
| 8.914300E+09 | -1.331104E+01 | -1.547969E+02 | -4.786133E+00 | -1.737500E+02 |
| 8.963650E+09 | -1.361865E+01 | -1.536250E+02 | -4.798340E+00 | 1.742500E+02 |
| 9.013000E+09 | -1.381641E+01 | -1.527891E+02 | -4.775635E+00 | 1.619062E+02 |
| 9.062350E+09 | -1.380615E+01 | -1.515703E+02 | -4.800781E+00 | 1.497031E+02 |
| 9.111700E+09 | -1.373242E+01 | -1.499375E+02 | -4.836914E+00 | 1.376094E+02 |
| 9.161050E+09 | -1.355566E+01 | -1.488359E+02 | -4.891113E+00 | 1.252734E+02 |
| 9.210400E+09 | -1.322021E+01 | -1.479609E+02 | -4.928711E+00 | 1.132891E+02 |
| 9.259750E+09 | -1.270215E+01 | -1.481172E+02 | -5.010742E+00 | 1.012812E+02 |
| 9.309100E+09 | -1.203809E+01 | -1.489531E+02 | -5.064697E+00 | 8.944921E+01 |
| 9.358450E+09 | -1.155811E+01 | -1.522578E+02 | -5.105957E+00 | 7.751171E+01 |
| 9.407800E+09 | -1.130176E+01 | -1.580078E+02 | -5.157959E+00 | 6.583202E+01 |
| 9.457150E+09 | -1.133154E+01 | -1.622813E+02 | -5.189453E+00 | 5.377539E+01 |
| 9.506500E+09 | -1.170020E+01 | -1.645547E+02 | -5.212402E+00 | 4.197851E+01 |
| 9.555850E+09 | -1.201904E+01 | -1.656016E+02 | -5.236084E+00 | 2.982617E+01 |
| 9.605200E+09 | -1.221240E+01 | -1.653828E+02 | -5.271729E+00 | 1.774121E+01 |
| 9.654550E+09 | -1.226123E+01 | -1.651562E+02 | -5.302246E+00 | 5.401123E+00 |
| 9.703900E+09 | -1.215479E+01 | -1.641328E+02 | -5.390869E+00 | -6.848633E+00 |
| 9.753250E+09 | -1.202832E+01 | -1.629453E+02 | -5.468994E+00 | -1.928418E+01 |
| 9.802600E+09 | -1.183154E+01 | -1.611484E+02 | -5.559326E+00 | -3.046679E+01 |
| 9.851950E+09 | -1.155322E+01 | -1.586016E+02 | -5.650879E+00 | -4.074219E+01 |
| 9.901300E+09 | -1.113818E+01 | -1.558516E+02 | -5.763428E+00 | -4.977148E+01 |
| 9.950650E+09 | -1.057715E+01 | -1.525781E+02 | -5.854492E+00 | -5.781445E+01 |

| | | | | |
|---|---|---|---|---|
| 1.000000E+10 | -9.929199E+00 | -1.506328E+02 | -5.962402E+00 | -6.451953E+01 |

## A.14. 130-mil wide M-shaped structure with 2S spacing

| Frequency | S11 (dB) | S11 (Phase) | S21 (dB) | S21 (Phase) |
|---|---|---|---|---|
| 1.300000E+08 | -2.078906E+01 | -1.528437E+02 | -1.282043E-01 | -5.260937E+01 |
| 1.793500E+08 | -2.035449E+01 | -1.605469E+02 | -1.454773E-01 | -5.971484E+01 |
| 2.287000E+08 | -1.997461E+01 | -1.695234E+02 | -1.615067E-01 | -6.800390E+01 |
| 2.780500E+08 | -1.969629E+01 | -1.797188E+02 | -1.784134E-01 | -7.746875E+01 |
| 3.274000E+08 | -1.956055E+01 | 1.688281E+02 | -1.925125E-01 | -8.814453E+01 |
| 3.767500E+08 | -1.963476E+01 | 1.561094E+02 | -2.093201E-01 | -1.000000E+02 |
| 4.261000E+08 | -2.004883E+01 | 1.423906E+02 | -2.245255E-01 | -1.130625E+02 |
| 4.754500E+08 | -2.130762E+01 | 1.294297E+02 | -2.416153E-01 | -1.261601E+02 |
| 5.248000E+08 | -2.322266E+01 | 1.268242E+02 | -2.577820E-01 | -1.392500E+02 |
| 5.741500E+08 | -2.429004E+01 | 1.271836E+02 | -2.748260E-01 | -1.523516E+02 |
| 6.235000E+08 | -2.496484E+01 | 1.280625E+02 | -2.861328E-01 | -1.654844E+02 |
| 6.728500E+08 | -2.542383E+01 | 1.291328E+02 | -3.030701E-01 | -1.786797E+02 |
| 7.222000E+08 | -2.567773E+01 | 1.301484E+02 | -3.198395E-01 | 1.681484E+02 |
| 7.715500E+08 | -2.577929E+01 | 1.313359E+02 | -3.380280E-01 | 1.549531E+02 |
| 8.209000E+08 | -2.573535E+01 | 1.323750E+02 | -3.634338E-01 | 1.417344E+02 |
| 8.702500E+08 | -2.550390E+01 | 1.334141E+02 | -3.887939E-01 | 1.285156E+02 |
| 9.196000E+08 | -2.508984E+01 | 1.345547E+02 | -4.114380E-01 | 1.152656E+02 |
| 9.689500E+08 | -2.438672E+01 | 1.353281E+02 | -4.356842E-01 | 1.019961E+02 |
| 1.018300E+09 | -2.312109E+01 | 1.354297E+02 | -4.588318E-01 | 8.878124E+01 |
| 1.067650E+09 | -2.147754E+01 | 1.254375E+02 | -4.829102E-01 | 7.547656E+01 |
| 1.117000E+09 | -2.092090E+01 | 1.126914E+02 | -4.985199E-01 | 6.218359E+01 |
| 1.166350E+09 | -2.107031E+01 | 1.000898E+02 | -5.216675E-01 | 4.888085E+01 |
| 1.215700E+09 | -2.182031E+01 | 8.863281E+01 | -5.395813E-01 | 3.556250E+01 |
| 1.265050E+09 | -2.321289E+01 | 8.134766E+01 | -5.521851E-01 | 2.216211E+01 |
| 1.314400E+09 | -2.447754E+01 | 7.857422E+01 | -5.651245E-01 | 8.727051E+00 |
| 1.363750E+09 | -2.534765E+01 | 7.769140E+01 | -5.741272E-01 | -4.743408E+00 |
| 1.413100E+09 | -2.604101E+01 | 7.783984E+01 | -5.840454E-01 | -1.825000E+01 |
| 1.462450E+09 | -2.659765E+01 | 7.807812E+01 | -6.024475E-01 | -3.177832E+01 |
| 1.511800E+09 | -2.695898E+01 | 7.848827E+01 | -6.213989E-01 | -4.534375E+01 |
| 1.561150E+09 | -2.725879E+01 | 7.913280E+01 | -6.403809E-01 | -5.898438E+01 |
| 1.610500E+09 | -2.743750E+01 | 7.943749E+01 | -6.608276E-01 | -7.260156E+01 |
| 1.659850E+09 | -2.747363E+01 | 7.968750E+01 | -6.902466E-01 | -8.630077E+01 |
| 1.709200E+09 | -2.731543E+01 | 7.930469E+01 | -7.169800E-01 | -1.000430E+02 |
| 1.758550E+09 | -2.688086E+01 | 7.719531E+01 | -7.490845E-01 | -1.138008E+02 |
| 1.807900E+09 | -2.613965E+01 | 7.063281E+01 | -7.854919E-01 | -1.275703E+02 |
| 1.857250E+09 | -2.574512E+01 | 5.900585E+01 | -8.282776E-01 | -1.413750E+02 |
| 1.906600E+09 | -2.589941E+01 | 4.450391E+01 | -8.710938E-01 | -1.551719E+02 |
| 1.955950E+09 | -2.617676E+01 | 2.749121E+01 | -9.259033E-01 | -1.690391E+02 |
| 2.005300E+09 | -2.645020E+01 | 9.934082E+00 | -9.719543E-01 | 1.770391E+02 |
| 2.054650E+09 | -2.661230E+01 | -8.876953E+00 | -1.032349E+00 | 1.631094E+02 |
| 2.104000E+09 | -2.674902E+01 | -2.840723E+01 | -1.100891E+00 | 1.491641E+02 |
| 2.153350E+09 | -2.674219E+01 | -4.487305E+01 | -1.144348E+00 | 1.352813E+02 |
| 2.202700E+09 | -2.623047E+01 | -6.201562E+01 | -1.193420E+00 | 1.213672E+02 |

| | | | | |
|---|---|---|---|---|
| 2.252050E+09 | -2.544140E+01 | -7.938281E+01 | -1.249451E+00 | 1.073555E+02 |
| 2.301400E+09 | -2.438183E+01 | -9.663671E+01 | -1.305298E+00 | 9.335546E+01 |
| 2.350750E+09 | -2.304394E+01 | -1.135469E+02 | -1.371399E+00 | 7.937890E+01 |
| 2.400100E+09 | -2.150000E+01 | -1.300859E+02 | -1.442871E+00 | 6.539453E+01 |
| 2.449450E+09 | -1.975586E+01 | -1.453203E+02 | -1.515747E+00 | 5.136913E+01 |
| 2.498800E+09 | -1.801562E+01 | -1.590781E+02 | -1.595703E+00 | 3.747070E+01 |
| 2.548150E+09 | -1.631933E+01 | -1.724141E+02 | -1.678589E+00 | 2.359668E+01 |
| 2.597500E+09 | -1.483350E+01 | 1.754844E+02 | -1.784485E+00 | 9.923340E+00 |
| 2.646850E+09 | -1.332080E+01 | 1.636641E+02 | -1.862183E+00 | -3.911133E+00 |
| 2.696200E+09 | -1.192725E+01 | 1.490313E+02 | -1.968689E+00 | -1.744433E+01 |
| 2.745550E+09 | -1.102539E+01 | 1.349453E+02 | -2.093628E+00 | -3.104394E+01 |
| 2.794900E+09 | -1.032813E+01 | 1.212461E+02 | -2.170410E+00 | -4.434179E+01 |
| 2.844250E+09 | -9.840332E+00 | 1.081016E+02 | -2.278809E+00 | -5.749218E+01 |
| 2.893600E+09 | -9.474609E+00 | 9.499218E+01 | -2.344849E+00 | -7.051171E+01 |
| 2.942950E+09 | -9.239746E+00 | 8.192968E+01 | -2.397095E+00 | -8.343750E+01 |
| 2.992300E+09 | -9.204590E+00 | 6.867188E+01 | -2.414307E+00 | -9.636719E+01 |
| 3.041650E+09 | -9.398438E+00 | 5.543945E+01 | -2.408081E+00 | -1.092383E+02 |
| 3.091000E+09 | -9.832520E+00 | 4.248242E+01 | -2.390503E+00 | -1.220781E+02 |
| 3.140350E+09 | -1.048682E+01 | 3.002246E+01 | -2.331177E+00 | -1.351641E+02 |
| 3.189700E+09 | -1.141064E+01 | 1.825488E+01 | -2.262939E+00 | -1.480703E+02 |
| 3.239050E+09 | -1.265479E+01 | 6.984375E+00 | -2.190552E+00 | -1.614063E+02 |
| 3.288400E+09 | -1.429736E+01 | -1.693298E+00 | -2.081909E+00 | -1.746094E+02 |
| 3.337750E+09 | -1.610937E+01 | -5.053711E+00 | -2.017944E+00 | 1.720156E+02 |
| 3.387100E+09 | -1.754395E+01 | -6.542480E+00 | -1.913208E+00 | 1.584453E+02 |
| 3.436450E+09 | -1.870019E+01 | -6.771729E+00 | -1.845093E+00 | 1.447266E+02 |
| 3.485800E+09 | -1.972754E+01 | -6.375000E+00 | -1.771118E+00 | 1.309766E+02 |
| 3.535150E+09 | -2.056055E+01 | -5.859863E+00 | -1.730774E+00 | 1.172812E+02 |
| 3.584500E+09 | -2.127539E+01 | -4.652832E+00 | -1.700745E+00 | 1.034414E+02 |
| 3.633850E+09 | -2.191406E+01 | -3.490967E+00 | -1.676392E+00 | 8.957811E+01 |
| 3.683200E+09 | -2.243555E+01 | -2.721924E+00 | -1.660278E+00 | 7.579296E+01 |
| 3.732550E+09 | -2.299219E+01 | -2.135498E+00 | -1.676758E+00 | 6.204883E+01 |
| 3.781900E+09 | -2.346875E+01 | -9.063721E-02 | -1.678040E+00 | 4.829296E+01 |
| 3.831250E+09 | -2.384082E+01 | 2.345581E+00 | -1.688110E+00 | 3.453125E+01 |
| 3.880600E+09 | -2.398535E+01 | 2.102417E+00 | -1.695557E+00 | 2.074707E+01 |
| 3.929950E+09 | -2.419922E+01 | 1.738586E+00 | -1.715698E+00 | 6.985840E+00 |
| 3.979300E+09 | -2.461328E+01 | 2.230225E+00 | -1.731079E+00 | -6.791016E+00 |
| 4.028650E+09 | -2.511133E+01 | 2.548828E+00 | -1.754578E+00 | -2.065625E+01 |
| 4.078000E+09 | -2.559473E+01 | 3.494995E+00 | -1.776428E+00 | -3.457031E+01 |
| 4.127350E+09 | -2.619531E+01 | 4.822998E+00 | -1.800415E+00 | -4.846874E+01 |
| 4.176700E+09 | -2.687109E+01 | 6.573730E+00 | -1.834290E+00 | -6.248632E+01 |
| 4.226050E+09 | -2.757324E+01 | 1.179199E+01 | -1.869141E+00 | -7.657031E+01 |
| 4.275400E+09 | -2.798242E+01 | 2.034863E+01 | -1.901794E+00 | -9.074999E+01 |
| 4.324750E+09 | -2.782812E+01 | 2.857129E+01 | -1.958618E+00 | -1.049883E+02 |
| 4.374100E+09 | -2.712109E+01 | 3.480664E+01 | -2.025635E+00 | -1.192188E+02 |
| 4.423450E+09 | -2.633301E+01 | 3.884570E+01 | -2.107910E+00 | -1.335156E+02 |
| 4.472800E+09 | -2.567578E+01 | 4.169335E+01 | -2.182617E+00 | -1.478672E+02 |
| 4.522150E+09 | -2.507813E+01 | 4.298047E+01 | -2.269409E+00 | -1.622344E+02 |
| 4.571500E+09 | -2.443262E+01 | 4.420507E+01 | -2.366821E+00 | -1.766328E+02 |
| 4.620850E+09 | -2.395117E+01 | 4.574804E+01 | -2.470947E+00 | 1.688906E+02 |

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|---|---|---|---|---|
| 4.670200E+09 | -2.347656E+01 | 4.705078E+01 | -2.572632E+00 | 1.543516E+02 |
| 4.719550E+09 | -2.282617E+01 | 4.911327E+01 | -2.686157E+00 | 1.398359E+02 |
| 4.768900E+09 | -2.205566E+01 | 5.022655E+01 | -2.811768E+00 | 1.253281E+02 |
| 4.818250E+09 | -2.121582E+01 | 4.984179E+01 | -2.941406E+00 | 1.106992E+02 |
| 4.867600E+09 | -2.042675E+01 | 4.934960E+01 | -3.056641E+00 | 9.606249E+01 |
| 4.916950E+09 | -1.967578E+01 | 4.876758E+01 | -3.184692E+00 | 8.135937E+01 |
| 4.966300E+09 | -1.888281E+01 | 4.803905E+01 | -3.320068E+00 | 6.660546E+01 |
| 5.015650E+09 | -1.808691E+01 | 4.678906E+01 | -3.467529E+00 | 5.182031E+01 |
| 5.065000E+09 | -1.723340E+01 | 4.530469E+01 | -3.610840E+00 | 3.711523E+01 |
| 5.114350E+09 | -1.631738E+01 | 4.377930E+01 | -3.760376E+00 | 2.242383E+01 |
| 5.163700E+09 | -1.529004E+01 | 4.145312E+01 | -3.913208E+00 | 7.840088E+00 |
| 5.213050E+09 | -1.405518E+01 | 3.838672E+01 | -4.071533E+00 | -6.763672E+00 |
| 5.262400E+09 | -1.282813E+01 | 3.420312E+01 | -4.217285E+00 | -2.121484E+01 |
| 5.311750E+09 | -1.163428E+01 | 2.745703E+01 | -4.342285E+00 | -3.560156E+01 |
| 5.361100E+09 | -1.054883E+01 | 1.872070E+01 | -4.471436E+00 | -4.982031E+01 |
| 5.410450E+09 | -9.777832E+00 | 8.679199E+00 | -4.574951E+00 | -6.404297E+01 |
| 5.459800E+09 | -9.267578E+00 | -2.154785E+00 | -4.649414E+00 | -7.793750E+01 |
| 5.509150E+09 | -9.000000E+00 | -1.305469E+01 | -4.692139E+00 | -9.183203E+01 |
| 5.558500E+09 | -9.009766E+00 | -2.395215E+01 | -4.700684E+00 | -1.057070E+02 |
| 5.607850E+09 | -9.229004E+00 | -3.450976E+01 | -4.677734E+00 | -1.196445E+02 |
| 5.657200E+09 | -9.741211E+00 | -4.454883E+01 | -4.633057E+00 | -1.336562E+02 |
| 5.706550E+09 | -1.044141E+01 | -5.352929E+01 | -4.572998E+00 | -1.478047E+02 |
| 5.755900E+09 | -1.136719E+01 | -6.063867E+01 | -4.495850E+00 | -1.619609E+02 |
| 5.805250E+09 | -1.239111E+01 | -6.659765E+01 | -4.413330E+00 | -1.762344E+02 |
| 5.854600E+09 | -1.336670E+01 | -7.082421E+01 | -4.327148E+00 | 1.693828E+02 |
| 5.903950E+09 | -1.436084E+01 | -7.316796E+01 | -4.217041E+00 | 1.549687E+02 |
| 5.953300E+09 | -1.525439E+01 | -7.482031E+01 | -4.132324E+00 | 1.405313E+02 |
| 6.002650E+09 | -1.604492E+01 | -7.577734E+01 | -4.044678E+00 | 1.257539E+02 |
| 6.052000E+09 | -1.683887E+01 | -7.599999E+01 | -3.960205E+00 | 1.109844E+02 |
| 6.101350E+09 | -1.759766E+01 | -7.580859E+01 | -3.897339E+00 | 9.617188E+01 |
| 6.150700E+09 | -1.835840E+01 | -7.425390E+01 | -3.854858E+00 | 8.134375E+01 |
| 6.200050E+09 | -1.899609E+01 | -7.112109E+01 | -3.822021E+00 | 6.652344E+01 |
| 6.249400E+09 | -1.933105E+01 | -6.689843E+01 | -3.794434E+00 | 5.175195E+01 |
| 6.298750E+09 | -1.936523E+01 | -6.291601E+01 | -3.780640E+00 | 3.697266E+01 |
| 6.348100E+09 | -1.913183E+01 | -5.945117E+01 | -3.760986E+00 | 2.220703E+01 |
| 6.397450E+09 | -1.881836E+01 | -5.689843E+01 | -3.758911E+00 | 7.454102E+00 |
| 6.446800E+09 | -1.839160E+01 | -5.611133E+01 | -3.774292E+00 | -7.351318E+00 |
| 6.496150E+09 | -1.797949E+01 | -5.596874E+01 | -3.791626E+00 | -2.217773E+01 |
| 6.545500E+09 | -1.761035E+01 | -5.610742E+01 | -3.806519E+00 | -3.692773E+01 |
| 6.594850E+09 | -1.721972E+01 | -5.719921E+01 | -3.842529E+00 | -5.162499E+01 |
| 6.644200E+09 | -1.676953E+01 | -5.834374E+01 | -3.868652E+00 | -6.633203E+01 |
| 6.693550E+09 | -1.635156E+01 | -6.070507E+01 | -3.901733E+00 | -8.107813E+01 |
| 6.742900E+09 | -1.604394E+01 | -6.452734E+01 | -3.932617E+00 | -9.580078E+01 |
| 6.792250E+09 | -1.608789E+01 | -6.855859E+01 | -3.962524E+00 | -1.105898E+02 |
| 6.841600E+09 | -1.632129E+01 | -7.137890E+01 | -3.990845E+00 | -1.253555E+02 |
| 6.890950E+09 | -1.652051E+01 | -7.253124E+01 | -4.024902E+00 | -1.402891E+02 |
| 6.940300E+09 | -1.666308E+01 | -7.294922E+01 | -4.058838E+00 | -1.551875E+02 |
| 6.989650E+09 | -1.671777E+01 | -7.321484E+01 | -4.096680E+00 | -1.702188E+02 |
| 7.039000E+09 | -1.670410E+01 | -7.309765E+01 | -4.136475E+00 | 1.747734E+02 |

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|---|---|---|---|---|
| 7.088350E+09 | -1.666894E+01 | -7.298046E+01 | -4.202881E+00 | 1.596719E+02 |
| 7.137700E+09 | -1.655078E+01 | -7.251171E+01 | -4.254883E+00 | 1.446172E+02 |
| 7.187050E+09 | -1.639746E+01 | -7.203906E+01 | -4.337402E+00 | 1.295859E+02 |
| 7.236400E+09 | -1.617383E+01 | -7.176171E+01 | -4.401855E+00 | 1.144453E+02 |
| 7.285750E+09 | -1.583838E+01 | -7.112499E+01 | -4.455322E+00 | 9.949999E+01 |
| 7.335100E+09 | -1.539600E+01 | -7.083202E+01 | -4.537842E+00 | 8.442186E+01 |
| 7.384450E+09 | -1.489209E+01 | -7.165234E+01 | -4.581299E+00 | 6.926952E+01 |
| 7.433800E+09 | -1.445020E+01 | -7.323828E+01 | -4.657715E+00 | 5.425781E+01 |
| 7.483150E+09 | -1.406201E+01 | -7.522655E+01 | -4.739014E+00 | 3.899023E+01 |
| 7.532500E+09 | -1.370947E+01 | -7.676171E+01 | -4.799805E+00 | 2.372265E+01 |
| 7.581850E+09 | -1.336621E+01 | -7.826172E+01 | -4.887207E+00 | 8.683105E+00 |
| 7.631200E+09 | -1.296240E+01 | -8.003124E+01 | -4.991455E+00 | -6.342041E+00 |
| 7.680550E+09 | -1.253174E+01 | -8.167187E+01 | -5.112061E+00 | -2.148144E+01 |
| 7.729900E+09 | -1.208496E+01 | -8.355860E+01 | -5.178711E+00 | -3.651172E+01 |
| 7.779250E+09 | -1.154980E+01 | -8.571484E+01 | -5.309082E+00 | -5.099804E+01 |
| 7.828600E+09 | -1.097754E+01 | -8.865625E+01 | -5.458252E+00 | -6.611328E+01 |
| 7.877950E+09 | -1.038477E+01 | -9.289454E+01 | -5.517822E+00 | -8.056641E+01 |
| 7.927300E+09 | -9.881836E+00 | -9.820313E+01 | -5.644531E+00 | -9.512499E+01 |
| 7.976650E+09 | -9.637207E+00 | -1.043125E+02 | -5.712402E+00 | -1.095586E+02 |
| 8.026000E+09 | -9.595215E+00 | -1.103789E+02 | -5.759521E+00 | -1.238477E+02 |
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| 8.124700E+09 | -1.001904E+01 | -1.195742E+02 | -5.837402E+00 | -1.525469E+02 |
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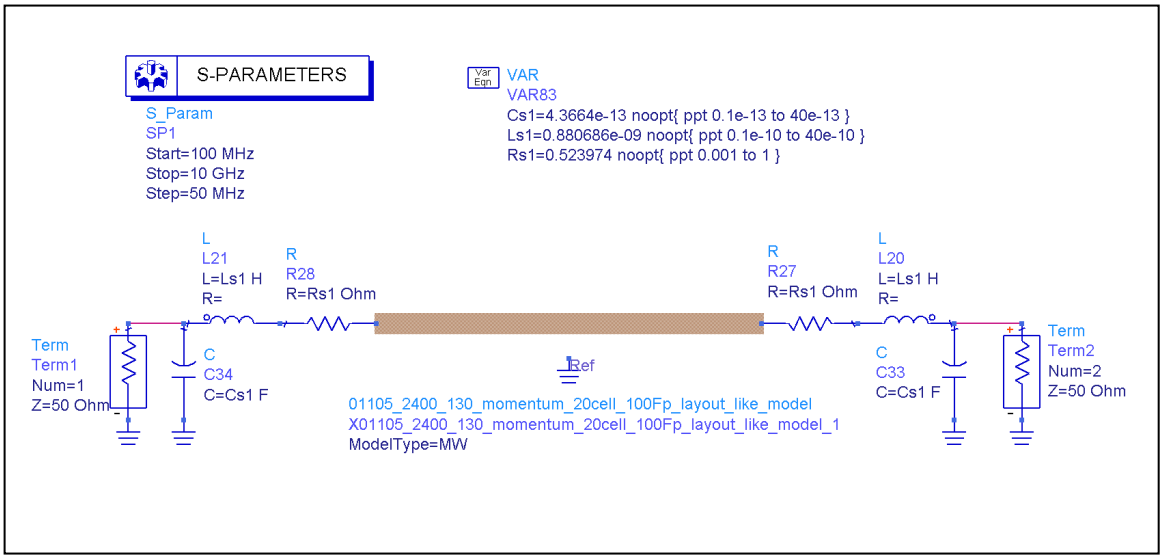
| 8.371450E+09 | -1.067773E+01 | -1.306406E+02 | -5.902100E+00 | 1.345078E+02 |
| 8.420800E+09 | -1.066748E+01 | -1.324687E+02 | -5.937012E+00 | 1.194375E+02 |
| 8.470150E+09 | -1.062549E+01 | -1.342266E+02 | -5.948730E+00 | 1.048945E+02 |
| 8.519500E+09 | -1.057471E+01 | -1.363203E+02 | -5.984863E+00 | 8.988672E+01 |
| 8.568850E+09 | -1.055859E+01 | -1.385156E+02 | -6.015869E+00 | 7.487499E+01 |
| 8.618200E+09 | -1.056152E+01 | -1.411797E+02 | -6.046875E+00 | 5.991211E+01 |
| 8.667550E+09 | -1.059717E+01 | -1.436094E+02 | -6.116455E+00 | 4.483007E+01 |
| 8.716900E+09 | -1.070166E+01 | -1.453906E+02 | -6.122314E+00 | 2.962988E+01 |
| 8.766250E+09 | -1.080811E+01 | -1.470469E+02 | -6.203857E+00 | 1.451270E+01 |
| 8.815600E+09 | -1.088184E+01 | -1.484766E+02 | -6.244629E+00 | -8.033752E-01 |
| 8.864950E+09 | -1.095166E+01 | -1.496172E+02 | -6.315918E+00 | -1.608984E+01 |
| 8.914300E+09 | -1.096484E+01 | -1.507344E+02 | -6.353516E+00 | -3.152148E+01 |
| 8.963650E+09 | -1.096338E+01 | -1.516875E+02 | -6.457520E+00 | -4.687304E+01 |
| 9.013000E+09 | -1.096045E+01 | -1.528516E+02 | -6.521729E+00 | -6.252148E+01 |
| 9.062350E+09 | -1.088428E+01 | -1.539766E+02 | -6.606689E+00 | -7.803905E+01 |
| 9.111700E+09 | -1.082129E+01 | -1.550781E+02 | -6.692383E+00 | -9.347656E+01 |
| 9.161050E+09 | -1.075879E+01 | -1.563672E+02 | -6.773926E+00 | -1.092266E+02 |
| 9.210400E+09 | -1.070459E+01 | -1.577266E+02 | -6.832031E+00 | -1.248008E+02 |
| 9.259750E+09 | -1.066260E+01 | -1.590234E+02 | -6.920898E+00 | -1.406328E+02 |
| 9.309100E+09 | -1.059521E+01 | -1.600234E+02 | -6.982178E+00 | -1.564141E+02 |
| 9.358450E+09 | -1.056250E+01 | -1.609922E+02 | -7.041992E+00 | -1.724219E+02 |
| 9.407800E+09 | -1.050586E+01 | -1.621875E+02 | -7.127930E+00 | 1.717187E+02 |
| 9.457150E+09 | -1.040625E+01 | -1.632266E+02 | -7.194336E+00 | 1.553984E+02 |

| | | | | |
|---|---|---|---|---|
| 9.506500E+09 | -1.034277E+01 | -1.640469E+02 | -7.255127E+00 | 1.393672E+02 |
| 9.555850E+09 | -1.027051E+01 | -1.648750E+02 | -7.332031E+00 | 1.230625E+02 |
| 9.605200E+09 | -1.019873E+01 | -1.655234E+02 | -7.418213E+00 | 1.069219E+02 |
| 9.654550E+09 | -1.007129E+01 | -1.661172E+02 | -7.499023E+00 | 9.054688E+01 |
| 9.703900E+09 | -9.883789E+00 | -1.665625E+02 | -7.604492E+00 | 7.429688E+01 |
| 9.753250E+09 | -9.646973E+00 | -1.669765E+02 | -7.692383E+00 | 5.794726E+01 |
| 9.802600E+09 | -9.454102E+00 | -1.682656E+02 | -7.775635E+00 | 4.325585E+01 |
| 9.851950E+09 | -9.367676E+00 | -1.698672E+02 | -7.835693E+00 | 2.999804E+01 |
| 9.901300E+09 | -9.378418E+00 | -1.712891E+02 | -7.897949E+00 | 1.827929E+01 |
| 9.950650E+09 | -9.458496E+00 | -1.722109E+02 | -7.913818E+00 | 7.903076E+00 |
| 1.000000E+10 | -9.612793E+00 | -1.725859E+02 | -7.947998E+00 | -8.102417E-01 |

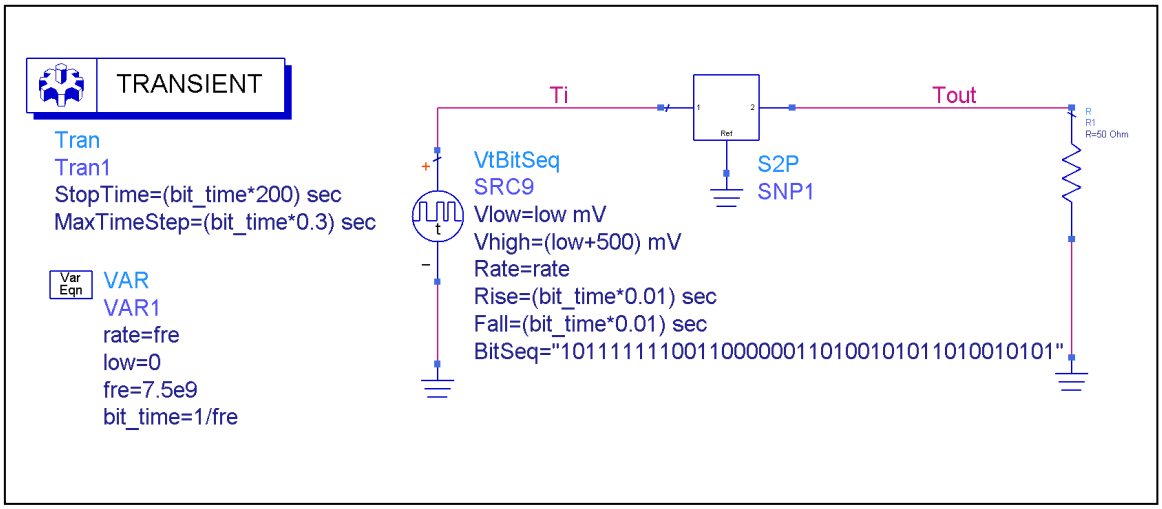
# APPENDIX B

# SIMULATION SCHEMATICS

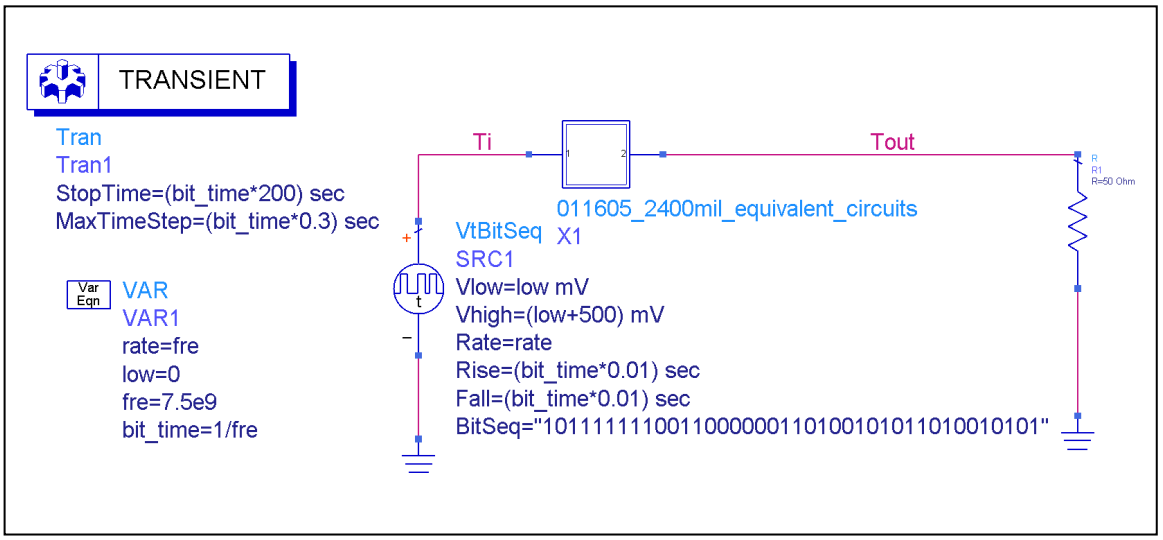
## B.1. Schematic of the momentum simulation with SMA connector



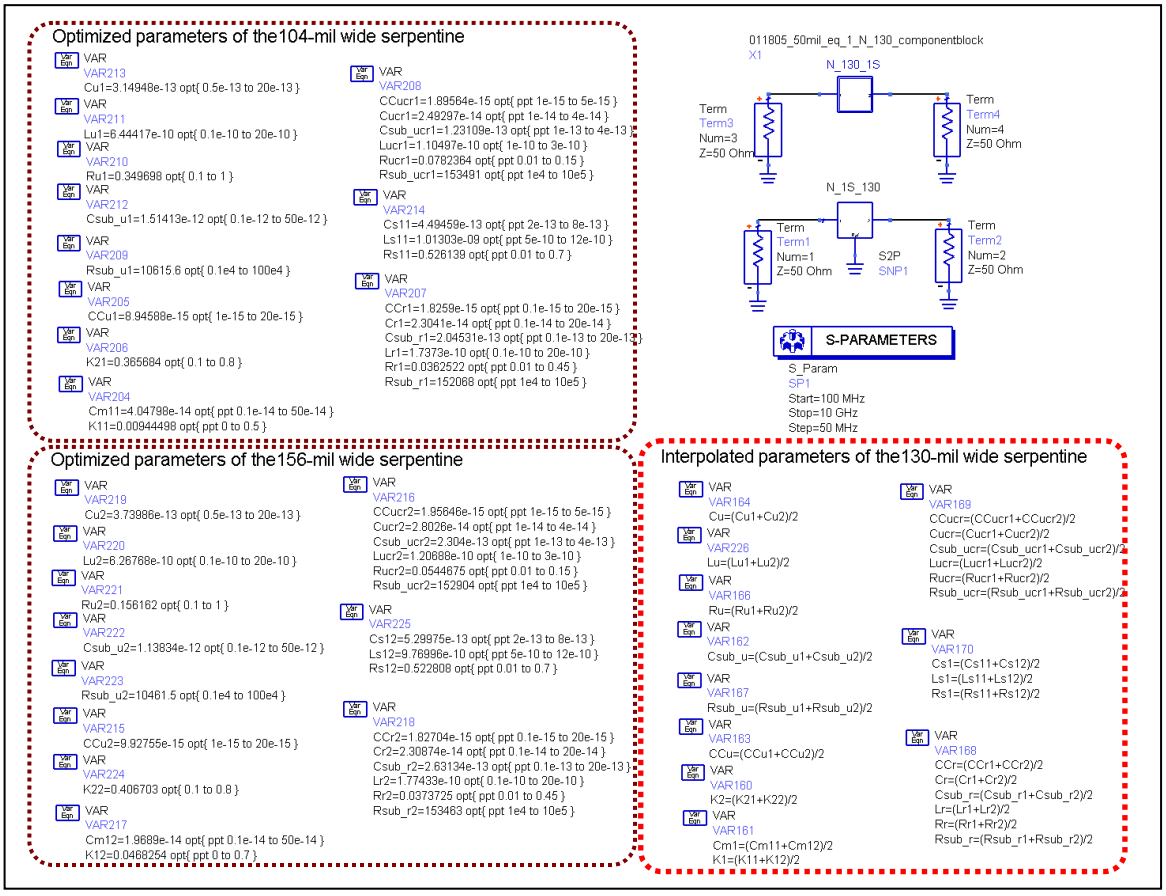

## B.2. Schematic of the transient simulation for eye diagram simulated from S-parameter data block



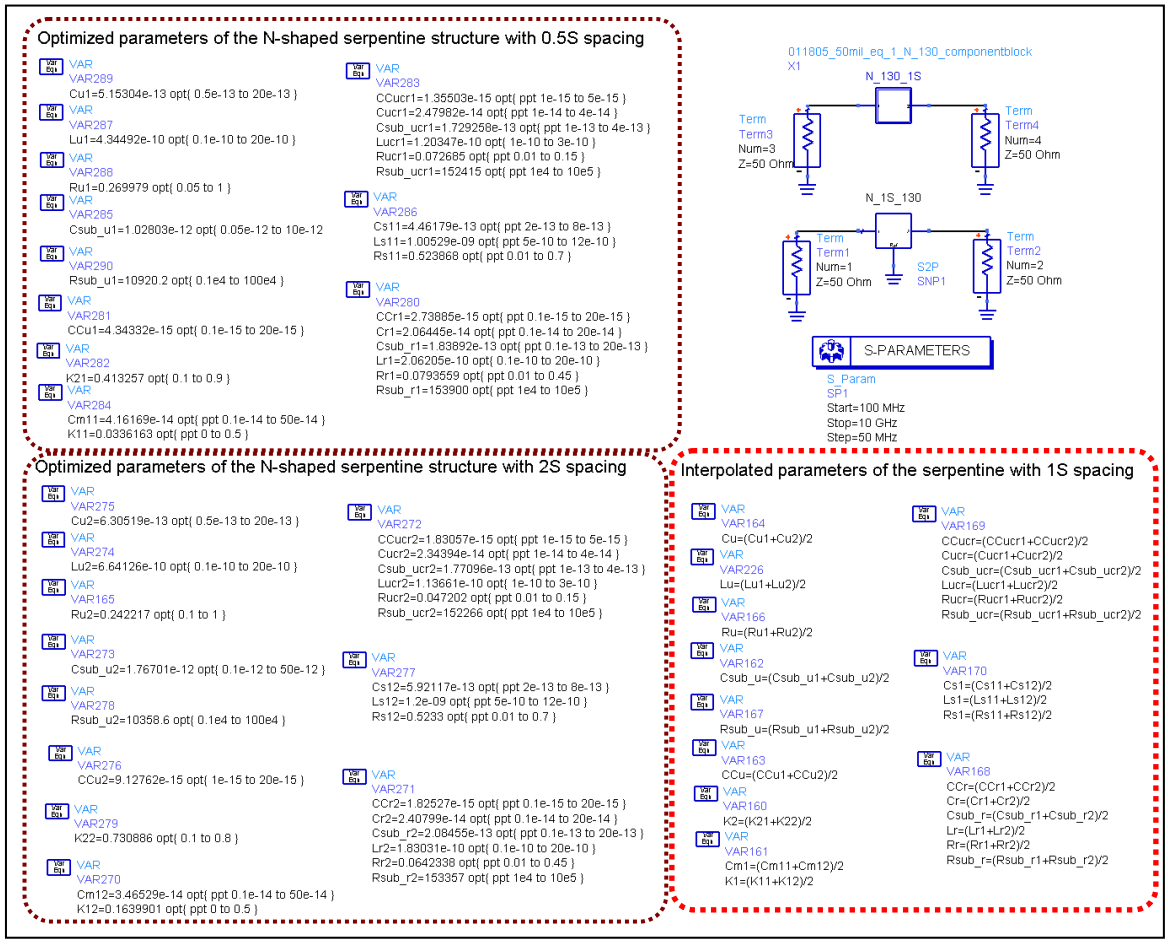
## B.3. Schematic of the transient simulation for eye diagram simulated from the predictive model




## B.4. Schematic of the width-interpolation



## B.5. Schematic of the spacing-interpolation



# APPENDIX C

# PUBLICATIONS


[1] **J. Shin**, C.-S. Seo, A. Chellappa, M. Brooke, A. Chattejce and N. M. Jokerst, "Comparison of electrical and optical interconnect," Electronic Components and Technology Conference, 2003.

[2] O. Bourdreaux, S.-Y. Cho, **J. Shin**, A. Chellappa, D. Schimmel, M. Brooke and N. M. Jokerst, "Optical chip-to-chip interconnects for memory systems," presented at Lasers and Electro-Optics Society, LEOS, the 16th Annual Meeting of the IEEE, 2003.

[3] C. Cha, **J. Shin**, Z. huang, N. M. Jokerst and M. Brooke, "High-Frequency Equivalent Circuit-Level Model of MSM PD for Optical Front-end Receiver Applications," presented at Asia Pacific Microwave conference, APMC 2003.

[4] N. M. Jokerst, T. K. Gaylord, E. Glytsis, M. A. Brooke, S. Cho, T. Nonaka, T. Suzuki, D. L. Geddis, **J. Shin**, R. Villalaz, J. Hall, A. Chellapa and M. Vrazel,"Planar lightwave integrated circuits with embedded actives for board and substrate level optical signal distribution," Advanced Packaging, IEEE Transactions on [see also Components, Packaging and Manufacturing Technology, Part B: Advanced Packaging, IEEE Transactions on], vol. 27, pp. 376-385, 2004.

[5] **J. Shin**, C. Cha, S. Cho, J. Kim, N. M. Jokerst and M. Brooke,"FR4 printed circuit board design for Giga-bits embedded optical interconnect applications," presented at Electronic Components and Technology, ECTC '04. Proceedings, 2004.

[6] **J. Shin**, S.-W. Seo, S.-Y. Cho, J. H. Kim, M. Brook and N. M. Jokerst,"Embedded photodetectors in polymer waveguides for optical interconnect integrated with a Si-Ge transimpedance amplifier circuit operating at 2.5 Gbit/s,"presented at Biophotonics/Optical Interconnects and VLSI Photonics/WBM Microcavities, Digest of the LEOS Summer Topical Meetings, 2004.

[7] J. H. Kim, **J. Shin,** C. Cha, N. Jokerst and M. Brooke, "Wideband multiple resonance small-signal laser diode model for the co-design of laser drive circuits," presented at the 47th Midwest Symposium, 2004.

[8] **J. Shin**, J. H. Kim, C. Cha, N. M. Jokerst and M. Brooke,"Rapid, Predictive Measurement-based Modeling for High Frequency Interconnect on FR4 Substrate," accepted at Electronic Components and Technology, 2005.

[9] J. H. Kim, **J. Shin**, C. Cha, N. M. Jokerst, and M. A. Brooke, "An Improved Wideband Laser Diode Lumped Element Equivalent Circuit Model for the Optoelectronic Circuit Design," submitted at Information and Communication Engineers (IEICE) Transactions on Information and Systems, 2005

# REFERENCES


[1] T. P. Smith III, "Semiconductor science: the fourth generation," Proceedings of the IEEE, vol. 79, pp. 1181-1187, 1991.

[2] W. E. Johnston, "High-speed, wide area, data intensive computing: a ten year retrospective," presented at High Performance Distributed Computing, 1998. Proceedings. The Seventh International Symposium on, 1998.

[3] Semiconductor Industry Association, International Tehnology Roadmap for Seimiconductor 2003 (http://public.itrs.net/Files/2003ITRS/Home2003.htm).

[4] D. A. B. Miller and H. M. Ozaktast, "Limit to the bit-rate capacity of electrical interconnects from the aspect ratio of the system architecture," Journal of Parallel and Distributed Computing, vol. 41, pp. 42-52, 1997.

[5] G. I. Yayla, J. Marchand, and S. C. Esener, "Speed and energy analysis of digital interconnections: comparison of on-chip, off-chip, and free-space technologies," Applied Optics, vol. 37, pp. 205-27, 1998.

[6] S. H. Hall, G. W. Hall, and J. A. McCall, High-speed digital system design: a handbook of interconnect theory and design practices, Chapter 4, *John Wiley & Sons, INC.,* ISBN 0-471-36090-2, 2000

[7] B. R. Rothermel, D. W. Helster and A. M. Sharf, "Practical guidelines for implementing 5Gbps in Copper Today, and the Roadmap to 10Gbps," AMP DesignCon, 2000.

[8] D. I. Amey and S. J. Horowitz, "Materials performance at frequencies up to 20 GHz," presented at IEMT/IMC Symposium, 1997., 1st [Joint International Electronic Manufacturing Symposium and the International Microelectronics Conference], 1997.

[9] J. Shin, C. Seo, A. Chellappa, M. Brooke, A. Chatterjee and N. M. Jokerst, "Comparison of electrical and optical interconnect," Electronic Component and Technology Conference, pp.1067-1072, 2003.

[10] D. M. Pozar, Microwave engineering 2nd, Chapter 3 and 4, *John Wiley & Sons, Inc.,* ISBN 0-471-17096-8, 1998.

[11] T. C. Edwards and M. B. Seer, Foundations of interconnect and microstrip design 3rd, Chapter 5, *John Wiley & Sons, Inc.,* ISBN 0-471-60701-0, 2000.

[12] Robert E. Collin, Electrical and computer engineering 2nd , Chapter 3, *McGraw-Hill, Inc.,* ISBN 0-07-011811-6, 1992.

[13] H. A. Wheeler, "Transmission-line properties of a strip on a dielectric sheet on a plane," Microwave Theory and Techniques, IEEE Transactions on, vol. 25, pp. 631-647, 1977.

[14] E. Hammerstad and O. Jensen, "Accurate models for microstrip computer-aided design," presented at Microwave Symposium Digest, 1980 MTT-S International, 1980.

[15] E. Hammerstad, "Equations for microstrip circuit design," proceeding european microwave conference , pp. 268-272, 1975.

[16] S. Y. Poh, W. C. Chew and J. A. Kong, "Approximate formulas for line capacitance and characteristic impedance of microstrip line, " IEEE transaction, vol. MTT-29, pp.135-142, 1981.

[17] M. A. R. Gunston and J. R. Weale, " Variation of microstrip impedance with strip thickness, " Electron Letter, vol. 5, p. 697, 1969.

[18] M. V. Schneider, "Microstrip lines for microwave integrated circuits, " Bell System Technical Journal, vol. 48, pp. 1422-1444, 1969.

[19] S. Cohn, "Problems in strip transmission lines," MTT-3, No. pp. 119-126, 1955.

[20] H. Howe, Strip line circuit design, Chapter 2, *Artech House, INC.,* ISBN 0-89-006020-7, 1974

[21] J. He, N. S. Nahman and S. M. Riad, "A causal skin-effect model of microstrip lines," presented at Microwave Symposium Digest, 1993., IEEE MTT-S International, 1993.

[22] S. Kim and D. P. Neikirk, "Compact equivalent circuit model for the skin effect," presented at Microwave Symposium Digest, 1996., IEEE MTT-S International, 1996.

[23] S. Mei and Y. I. Ismail, "Modeling skin effect with reduced decoupled R-L circuits," presented at Circuits and Systems, 2003. ISCAS '03. Proceedings of the 2003 International Symposium on, 2003.

[24] W.H. Hayt and J.A. Buck, Engineering electromagnetics, Chapter 11, *McGraw-Hill, Inc.,* ISBN 0-07-118162-8, 2001.

[25] V. Goldade, L. Pinchuk and Y. Voronezhtsev, "Electric polarization of polymers in metal-dielectric-metal systems," presented at Electrets, 1988. (ISE 6) Proceedings., 6th International Symposium on (IEEE Cat. No.88CH2593-2), 1988.

[26] C. T. A. Johnk, Engineering electromagnetic fields and waves, Chapter 3, *John Wiley & Sons, Inc.,* ISBN 0-471-44289-5, 1975.

[27] S. Ramo, J. R. Whinnery and T. V. Duzer, Fields and waves in communication electronics 3rd, Chapter 6, *John Wiley & Sons, Inc.,* ISBN 0-471-87130-3, 1993.

[28] S. J. Mumby and J. Yuan, " Dielectric properties of FR-4 Laminates as a function of thickness and the electrical frequency of the measurement," Journal of Electronic Materials, vol. 18, No. 2, 1989.

[29] L. Proekt and A. C. Cangellaris, "Investigation of the impact of conductor surface roughness on interconnect frequency-dependent ohmic loss," presented at Electronic Components and Technology Conference, 2003. Proceedings. 53rd, 2003.

[30] H. A. Wheeler, "Transmission-Line Properties of Parallel Wide Strips by a Conformal-Mapping Approximation," Microwave Theory and Techniques, IEEE Transactions on, vol. 12, pp. 280-289, 1964.

[31] J.-G. Yook, N. I. Dib and L. P. B. Ratehi, "Characterization of high frequency interconnects using finite difference time domain and finite element methods," Microwave Theory and Techniques, IEEE Transactions on, vol. 42, pp. 1727-1736, 1994.

[32] P. C. Cherry and M. F. Iskander, "FDTD analysis of high frequency electronic interconnection effects," Microwave Theory and Techniques, IEEE Transactions on, vol. 43, pp. 2445-2451, 1995.

[33] N. Orhanovic, R. Raghuram and N. Matsui, "Full wave analysis of planar interconnect structures using FDTD-SPICE," presented at Electronic Components and Technology Conference, 2001. Proceedings., 51st, 2001.

[34] T. V. Yioultsis, L. B. Proekt and A. C. Cangellaris, "An asymptotic FEM analysis for the electromagnetic modeling of interconnects and integrated RF passives for SiP and SoC designs," presented at Electronics Packaging Technology Conference, 2002. 4th, 2002.

[35] M. Bozzi, L. Perregrini, A. Alvarez Melcon, M. Guglielmi, and G. Conciauro, "MoM/BI-RME analysis of boxed MMICs with arbitrarily shaped metallizations," Microwave Theory and Techniques, IEEE Transactions on, vol. 49, pp. 2227-2234, 2001.

[36] Advanced Design System 2002 Momentum, Agilent Technologies, Feb. 2002.

[37] P. Argus and H. Singer, "New basis functions for connections between wire and surface structures for time domain method of moments," presented at Electromagnetic Compatibility, 2002 IEEE International Symposium on, 2002.

[38] A. E. Ruehli, "Equivalent circuit models for three-dimensional multiconductor systems," Microwave Theory and Techniques, IEEE Transactions on, vol. 22, pp. 216-221, 1974.

[39] H. Heeb and A. E. Ruehli, "Three-dimensional interconnect analysis using partial element equivalent circuits," Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on [see also Circuits and Systems I: Regular Papers, IEEE Transactions on], vol. 39, pp. 974-982, 1992.

[40] A. E. Ruehli and H. Heeb, "Circuit models for three-dimensional geometries including dielectrics," Microwave Theory and Techniques, IEEE Transactions on, vol. 40, pp. 1507-1516, 1992.

[41] G. Wollenberg and A. Gorisch, "Coupling of PEEC models with transmission line models for simulation of wiring structures," presented at Electromagnetic Compatibility, 1999 IEEE International Symposium on, 1999.

[42] C. Wollenberg and A. Gurisch, "Analysis of 3-D interconnect structures with PEEC using SPICE," Electromagnetic Compatibility, IEEE Transactions on, vol. 41, pp. 412-417, 1999.

[43] J. Cullum, A. Ruehli and T. Zhang, "A method for reduced-order modeling and simulation of large interconnect circuits and its application to PEEC models with retardation," Circuits and Systems II: Analog and Digital Signal Processing, IEEE Transactions on [see also Circuits and Systems II: Express Briefs, IEEE Transactions on], vol. 47, pp. 261-273, 2000.

[44] J. Ekman, "Experimental verification of PEEC based electric field simulations," presented at Electromagnetic Compatibility, 2001. EMC. 2001 IEEE International Symposium on, 2001.

[45] A. Rong, A. C. Cangellaris and L. Dong, "Comprehensive broadband electromagnetic modeling of on-chip interconnects with a surface discretization-based generalized PEEC model," presented at Electrical Performance of Electronic Packaging, 2003, 2003.

[46] G. Antonini, A. E. Ruehli and A. Haridass, "Including dispersive dielectrics in PEEC models," presented at Electrical Performance of Electronic Packaging, 2003.

[47] S. Sercu and L. Martens, "Accurate de-embedding of the contribution of the test boards to the high frequency characteristics of backplane connectors," presented at Electrical Performance of Electronic Packaging, 1997., IEEE 6th Topical Meeting on, 1997.

[48] E. F. Calandra, "Measurement-based modeling of microwave transistor package and test-fixture for device S-parameter deembedding," presented at Circuits and Systems, 1994., Proceedings of the 37th Midwest Symposium on, 1994.

[49] J. De Geest, S. Sercu, and J. Nadolny, "Electrical modeling of high speed interconnection links," presented at Electronic Components and Technology Conference, 2001. Proceedings., 51st, 2001.

[50] R. Poddar and M. Brooke, "Accurate, high speed modeling of integrated passive devices in multichip modules," Electrical Performance of Electronic Packaging, 1996., IEEE 5th Topical Meeting ,1996, pp 184 -186.

[51] Poddar, R., Moon, E.M., Brooke, M.A., and Jokerst, N.M., "Accurate, rapid, high frequency empirically based predictive modeling of arbitrary geometry planar resistive passive devices," IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part B: Advanced Packaging, pp. 177-183, Volume 21, Issue 2, May 1998

[52] H.T. Micheal, Scientific computing : An intorductory survey, 2nd , *McGrqw-Hill, Inc.,* ISBN 0-07-239910-4, 2002

[53] Advanced Design System 2002, Agilent Technologies, Feb. 2002.

[54] C. Tocci and H. Caulfield, Optical Interconnection – Foundation and Application, *KARTECH HOUSE,Inc.*, ISBN 0-890006-632-9, 1994

[55] E. K. Miller, "A selective survey of computational electromagnetics," Antennas and Propagation, IEEE Transactions on, vol. 36, pp. 1281-1305, 1988.

[56] D. Skirmont, "Optical Interconnection Backplane Technology for Terabit Routers", *Pluris*, Jan, 2000

[57] Agilent Technologies Application Note, Agilent Technologies and Communications: Six Decades of Measurement Contributions (http://cp.literature.agilent.com/litweb /pdf/5980-2090E.pdf).

[58] Jeff Hecht, Understanding Fiber Optics, *Prentice Hall, Inc.*, ISBN 0-256-10104-3, 1995.

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